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Smoke Management Photographic Guide – A Visual Aid for Communicating Smoke Impacts

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University of Idaho
College of Natural Resources

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands—as directed by Congress—to provide increasingly greater service to a growing Nation.

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Abstract

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When communicating emissions impacts with to the public, it can sometimes be difficult to quantitatively convey smoke concentrations. Regulators and land managers often refer to particulate matter concentrations in micrograms per cubic meter, but this may not be intuitive or meaningful to members of the public. The primary purpose of this guide is to serve as a tool for communicating potential particulate matter ($PM_{2.5}$) levels during wildfire events using visual representation. Examples of visibility impairment under various smoke concentrations and humidities have been modeled using the WinHaze program.

Keywords: air quality, regional haze, smoke management

Cooperators

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Contents

Introduction

When describing the impacts of emissions from wildland fire on air quality it is difficult to quantitatively assess smoke concentrations. Smoke is composed of a variety of chemical compounds, but regulators and land managers often focus on particulate matter (PM) owing to its effects on human health and visibility degradation. Particles in smoke generally range in size from 0.1 to 100 micrometers (μm) in diameter (Hardy et al. 2001). Particulate matter less than or equal to 10 μm in diameter (PM_{10}) and less than or equal to 2.5 μm in diameter ($PM_{2.5}$) are the most common size classes used in air quality measurement and monitoring. Particulate matter concentration is measured in units of micrograms per cubic meter ($\mu g \cdot m^{-3}$), but this may not be intuitive or meaningful to members of the public. The primary purpose of this guide is to serve as a tool for communicating the level of $PM_{2.5}$ by using visual representation.

Visibility is impacted by several factors, including the composition and concentration of wildland fire smoke. Particulate matter emitted from fire can contain ammonium nitrate (NH_4NO_3), ammonium sulfate ($(NH_4)_2SO_4$), and light absorbing carbon (LAC; Malm et al. 1994). The effect these compounds have on visibility can be magnified by relative humidity (RH), as water vapor binds to these particles and alters the way they absorb and reflect light (Malm et al. 2003). In addition, background levels of visibility vary geographically (Malm et al. 1994, Hand et al.

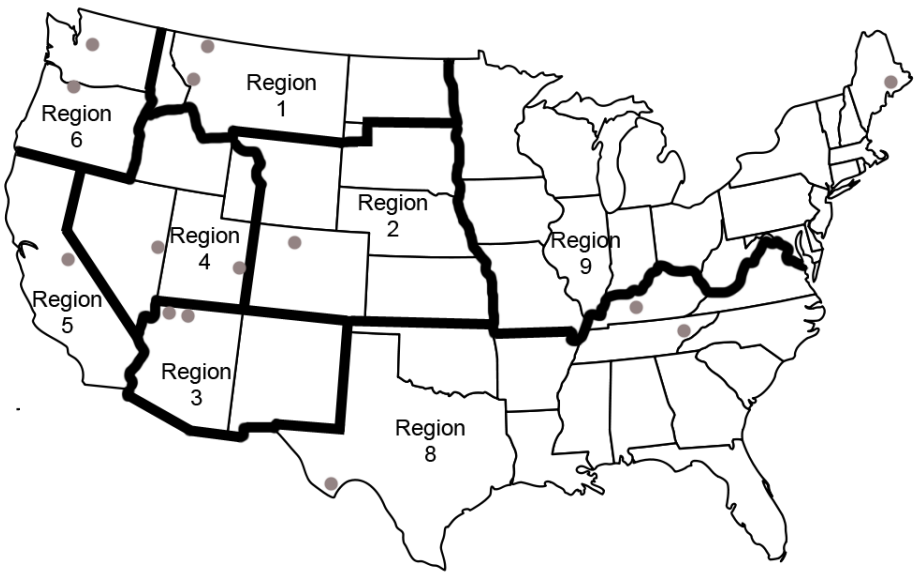

Figure 1—Map showing the location of U.S. Forest Service, Regions and photo site locations (grey dots). The images and data in this guide are intended to represent typical conditions in these regions.

R1: Selway-Bitterroot Wilderness (south), Glacier NP (north)
R2: Rocky Mountain NP
R3: Grand Canyon NP (both)
R4: Canyonlands NP (east), Great Basin NP (west)
R5: Yosemite NP
R6: Columbia River Gorge (south), Snoqualmie Pass (north)
R8: Great Smoky Mountains NP (east), Mammoth Cave NP (center), Big Bend NP (west)
R9: Acadia NP

This guide will help air quality regulators and land managers communicate $PM_{2.5}$ concentrations during wildland fires.

2014). This guide is intended to illustrate the effects of wildland fire smoke on visibility in U.S. Forest Service Regions 1-6, 8, and 9 (fig. 1). Due to the complex relationship between contrasts perceived by the naked eye, its relationship to visual range, and the subsequent particle concentration associated with those conditions, observed visual range approximations should be used as general indicators, not precise measurements.

This guide was developed with images from locations on National Park Service and U.S. Forest Service lands to assess visibility impairment associated with wildland fires. Images presented in this guide were generated by using WinHaze (Air Resource Specialists, Inc. 2013), a software tool developed to visualize the impacts of air pollutants on visibility.

Methods

To represent visual impacts from smoke in numerous locations across the United States this reference guide was generated using WinHaze imaging software version 2.9.9.1. (Air Resource Specialists, Inc. 2013). WinHaze incorporates several years of particulate monitoring data and images from National Parks and Wilderness Areas and simulates visibility based on those data and an equation to determine the reduction of visibility referred to as beta extinction (Hand and Malm 2006). The beta extinction equation and particulate monitoring data are products of the Interagency Monitoring of Protected Visual Environments (IMPROVE) program. Through the IMRPOVE program, stationary cameras and air quality monitoring equipment are stationed at several National Parks throughout the U.S. For full details on the IMPROVE monitoring network, methods equation for representing visibility impairment, please refer to the IMPROVE website (http://vista.cira.colostate.edu/improve/Default.htm).

The use of WinHaze allows for consistent visual representation of air quality under varying humidity, background pollutant, and $PM_{2.5}$ concentrations levels. Each example location in this guide contains a simulated baseline image to represent visual range under average particulate matter concentrations as found in the IMPROVE data contained in WinHaze. Also included are several images of simulated visual impairment from smoky conditions. Visual impairment from smoke was simulated first by establishing constant values for the constituents of PM 2.5 that are unlikely to change as the result of smoke from fires;

ammonium sulfate, ammonium nitrate, and fine soil were determined by using values recorded for the 20% worst visibility days. Organic carbon and black carbon were then increased to reflect increasing concentrations of smoke, as this carbon comprises nearly 75% of the emissions from forest fires (Andreae and Merlet 2001). The ratio of organic carbon to black carbon is represented by a 15.4:1 ratio based on estimates for wildland fire in non-tropical forests (Andreae and Merlet 2001). The coarse particulate inputs used to simulate each image were chosen based on the greater of two values: either the average value of the 20% worst monitored days, or 10% of the $PM_{2.5}$ concentration based on Ward and Hardy (1991). Based on the relationship between $PM_{2.5}$ and PM_{10} (Ward and Hardy 1991), elevated coarse particulates were represented to be 10% of the total $PM_{2.5}$ value (ammonium sulfate, ammonium nitrate, fine soil, organic carbon and black carbon).

The version of WinHaze used for this work includes the first version of the IMPROVE beta extinction equation, as described in Hand and Malm (2006). To improve the accuracy of the simulations presented here, a correction factor was applied to the organic carbon values prior to generating each image and visual range determination. The organic carbon correction factor accounts for hygroscopicity (based on Malm et al. 2005), such that the light scattering (total beta extinction) of organic carbon increased linearly by a factor of 1.2 at 80% RH relative to zero RH. Each photograph includes prominent landmarks with which to judge visual range. The distance between the camera locations and various landmarks was measured with Google Earth and verified by using location information from Air Resource Specialists, Inc.

Because RH impacts visibility and changes throughout the day and seasonally, a range of values were chosen to represent morning and afternoon monthly averages most likely to be present during the wildland fire season (May to September) in all locations in National Parks (EPA 2014). Because these data were unavailable for the chosen locations in Forest Service Region 6, meteorological station data were chosen from a location as geographically close to the available site as possible (NOAA 2014).

The $PM_{2.5}$ levels that were chosen for display in this guide, are those that are deemed as Good (<38 $\mu g \cdot m^{-3}$), Unhealthy for Sensitive Groups (89-138 $\mu g \cdot m^{-3}$), and Unhealthy (139-351 $\mu g \cdot m^{-3}$) for short periods of time

Public health officials may recomment different actions based on the concentration of smoke in the area.

(1-3 hours) based on the levels outlined in *Wildfire smoke: a guide for public health officials* (table 1; Lipsett et al. 2012). The mid-point of each range was chosen to represent each heath level: 19 μg · m^{-3} for Good, 114 μg · m^{-3} for Unhealthy for Sensitive Groups and 245 μg · m^{-3} for Unhealthy. These levels correspond to actions that need to be taken by public health officials, where Good requires no action, Unhealthy for Sensitive Groups merits warnings or alerts to those with heart or lung conditions, or other pertinent health issues, and Unhealthy requires that all people should be notified, regardless of health status (Lipsett et al. 2012). The specific values were chosen because they are sufficiently different as to be easily discernable to the naked eye.

Table 1—Photographs and visual range estimates representing the PM concentration mid-points of the Good (19 *μg · m*$^{-3}$), Unhealthy for Sensitive Groups (114 *μg · m*$^{-3}$), and Unhealthy (245 *μg · m*$^{-3}$) categories. Adapted from Lipsett et al. (2012) and EPA (2013)

Air Quality	PM_{10} or $PM_{2.5}$ Concentration[a]	Actions to protect one's health from PM_{10} or $PM_{2.5}$ pollution
	μg · m^{-3}	
Good	0-38	- None
Moderate	39-88	- Unusually sensitive people should consider reducing prolonged or heavy exertion
Unhealthy for Sensitive Groups	89-138	- People with heart or lung disease, children, and older adults should reduce prolonged or heavy outdoor exertion - Everyone else should limit prolonged or heavy exertion
Unhealthy	139-351	- People with heart or lung disease, children, and older adults should avoid all physical activity outdoors - Everyone else should avoid prolonged or heavy exertion
Very Unhealthy	>351	- People with heart or lung disease, children, and older adults should remain indoors and keep activity levels low - Everyone else should avoid all physical activity outdoors

[a]Particulate Matter concentrations are 1- to 3-hr averages

Using This Guide

Each set of photographs in this guide is preceded by a description of the air quality data for the site depicted. This includes the date range and

number of sampling days of particulate matter data used by WinHaze, the source for the RH data, a table listing the constituents of smoke (both $PM_{2.5}$ and PM_{10}) represented in the images, and a table listing all of the visible range distances for each $PM_{2.5}$ concentration and RH level.

To use this guide to represent $PM_{2.5}$ concentration, select the Region and location that best matches the terrain and RH conditions of the location you are assessing and compare your line of sight with landmarks that are located at distances that are similar to those shown in the photographs. For each location, images are included that represent baseline (smoke free), Good (19 $\mu g \cdot m^{-3}$), Unhealthy for Sensitive Groups (114 $\mu g \cdot m^{-3}$), and Unhealthy (245 $\mu g \cdot m^{-3}$) conditions, except in cases where no distinction could be made between photographs, which sometimes occurs at the higher $PM_{2.5}$ concentration levels.

Tables documenting the constituents of particulate matter (PM) at different concentration levels, and visual range at different PM concentration and relative humidity levels are included for each set of photographs.

Limitations

Visual range is simulated based on scientific analysis of air quality data and the constituents of wildland fire smoke. Images included in this guide were generated independently of sun angle, which does affect visibility. Those seeking more information on the influence of sun angle on visibility can refer to: Malm and Schitchtel (2013) and Middleton (1968). It should also be noted that the $PM_{2.5}$ concentration levels for Good, Unhealthy for Sensitive Groups, and Unhealthy conditions shown in the photographs are based on average $PM_{2.5}$ levels over a 1-3 hour period, not the instantaneous $PM_{2.5}$ concentration, and that visual range can change relatively rapidly.

English Equivalents

When you know:	Multiply by:	To find:
Microns (μm)	0.039	Mil
Kilometers (km)	0.62	Miles

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U.S. Forest Service, Region 1 –Glacier National Park & Selway-Bitterroot Wilderness, MT

Particulate data from 1,037 days of sampling (March 1988 to May 1999) at Glacier National Park were chosen to represent baseline and elevated regional air quality concentrations (table 2). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 3) and illustrated for the Selway-Bitterroot Wilderness and Glacier National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Glacier National Park (≥40% RH; EPA 2014) and Missoula, MT (<40% RH; NOAA 2014).

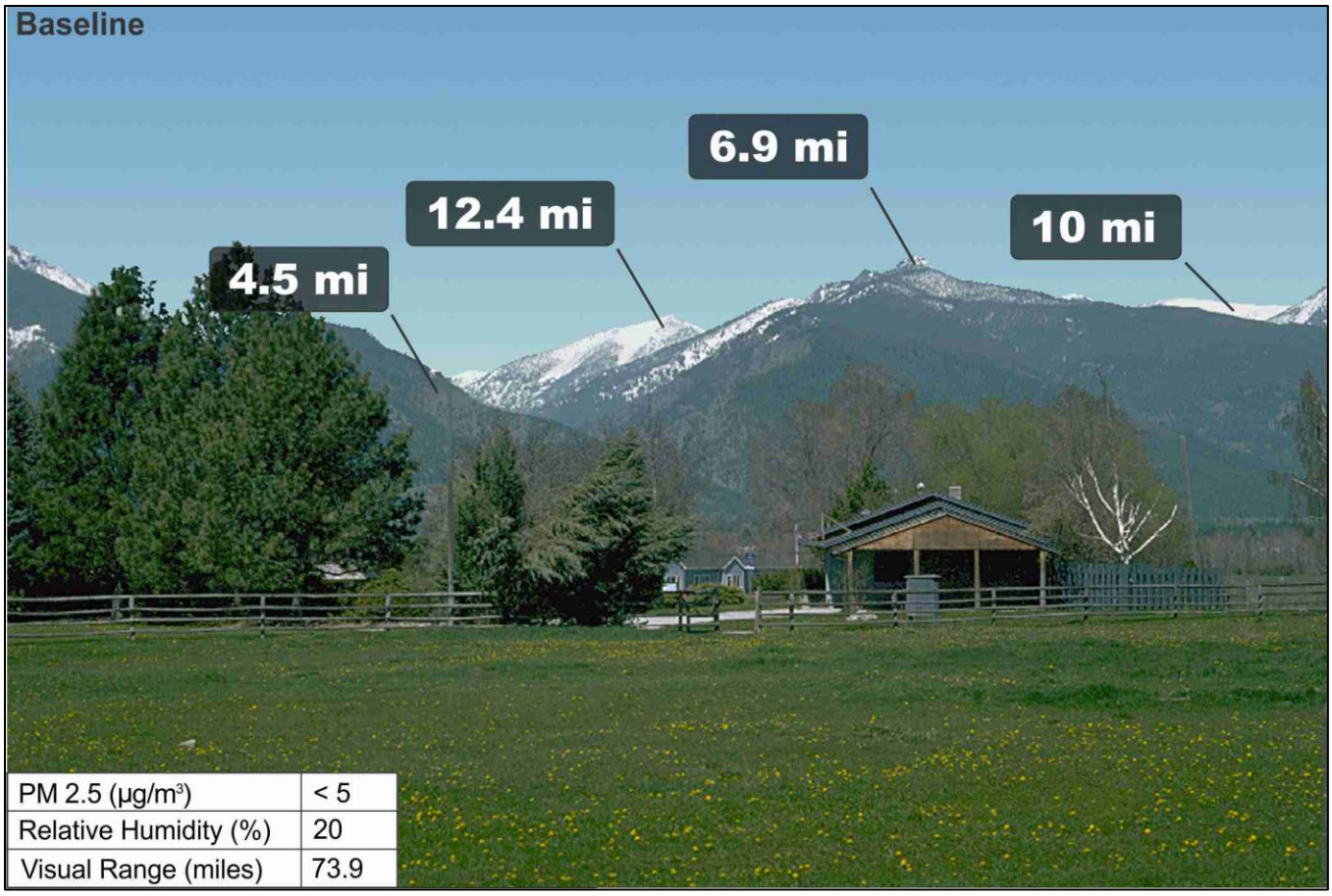
Table 2—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in the Selway-Bitterroot Wilderness and Glacier National Park, MT

Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	0.96	1.29	1.29	1.29
Ammonium nitrate	0.30	0.61	0.61	0.61
Organic carbon	2.67	14.95	104.14	227.13
LAC/Black carbon	0.43	0.97	6.78	14.79
Fine soil	0.58	1.19	1.19	1.19
Coarse mass	6.12	10.21	11.40	24.50

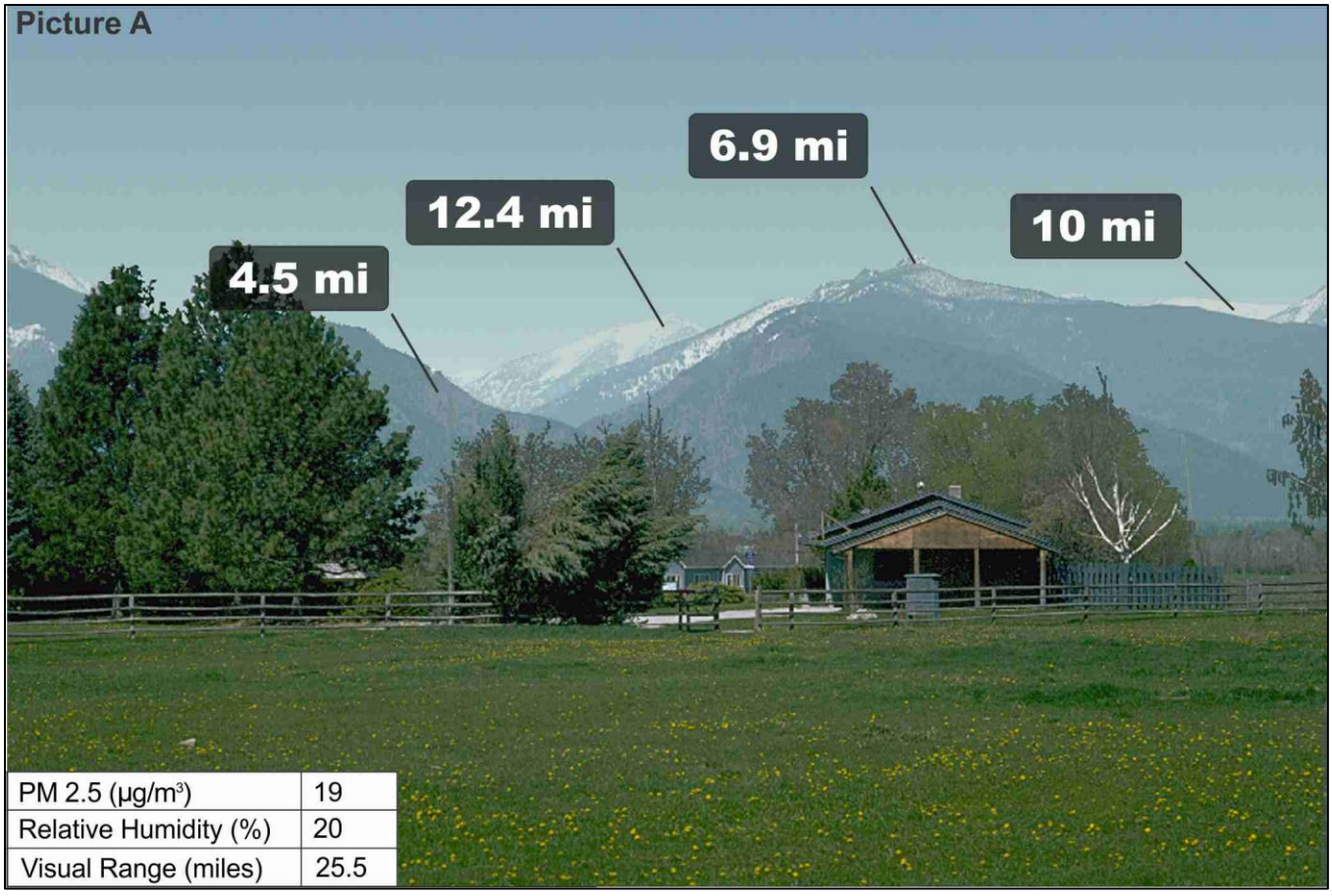
Table 3—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in the Selway-Bitterroot Wilderness (SBW) and Glacier National Park (GNP), MT

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline, SBW)	20	73.9	119.0
(baseline, GNP)	40	72.7	117.0
19 (picture A, SBW)	20	25.5	41.0
	30	25.1	40.4
(picture A, GNP)	40	24.6	39.6
	60	23.1	37.2
	80	21.3	34.3
	90	19.9	32.1
114 (picture B, SBW)	20	4.6	7.4
	30	4.5	7.3
(picture B, GNP)	40	4.4	7.1
	60	4.2	6.8
	80	4.0	6.5
	90	3.9	6.3
245 (picture C, SBW)	20-30	2.1	3.4
(picture C, GNP)	40	2.1	3.3
	50-60	2.0	3.2
	70-90	1.9	3.1

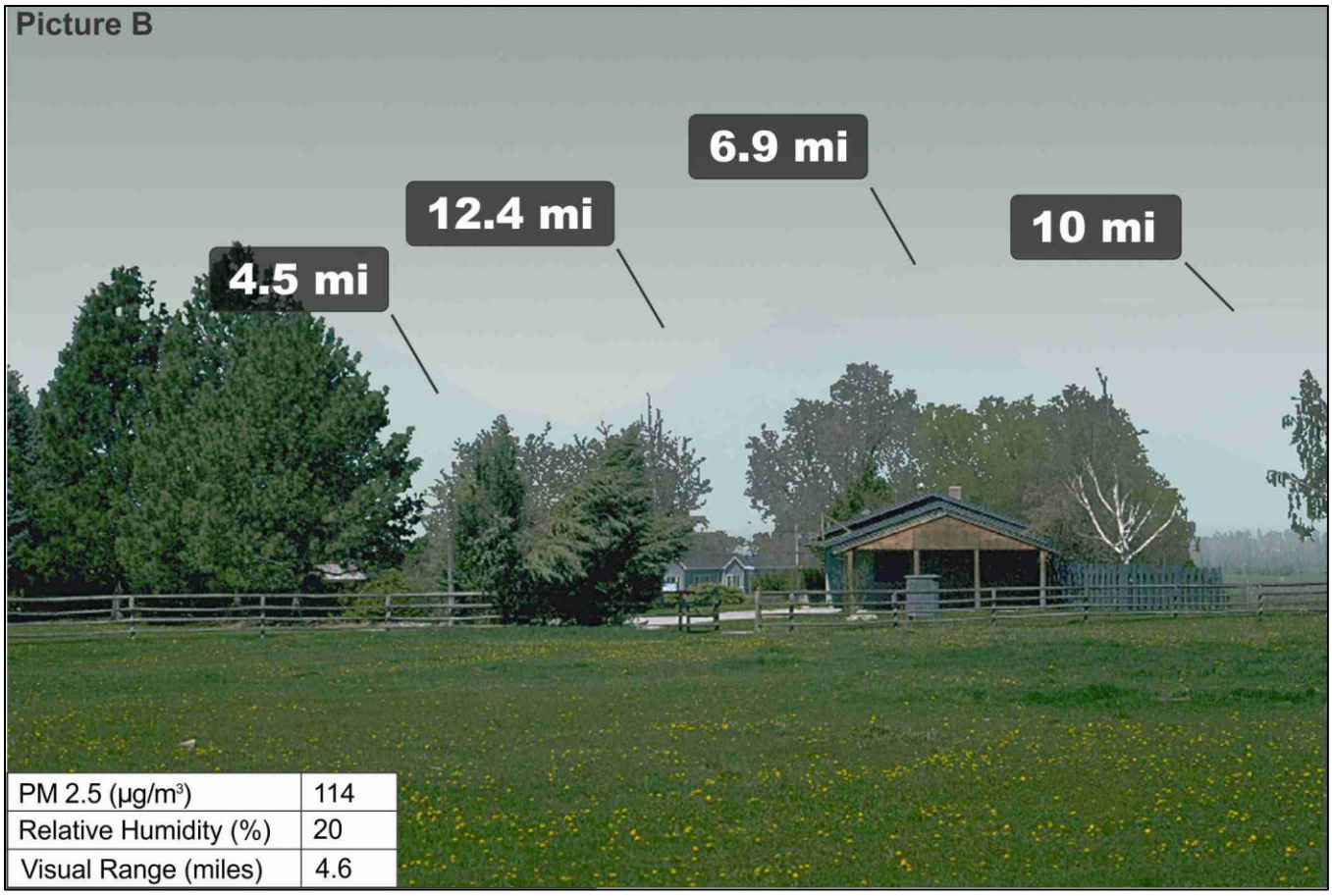
SELWAY-BITTERROOT WILDERNESS, MT

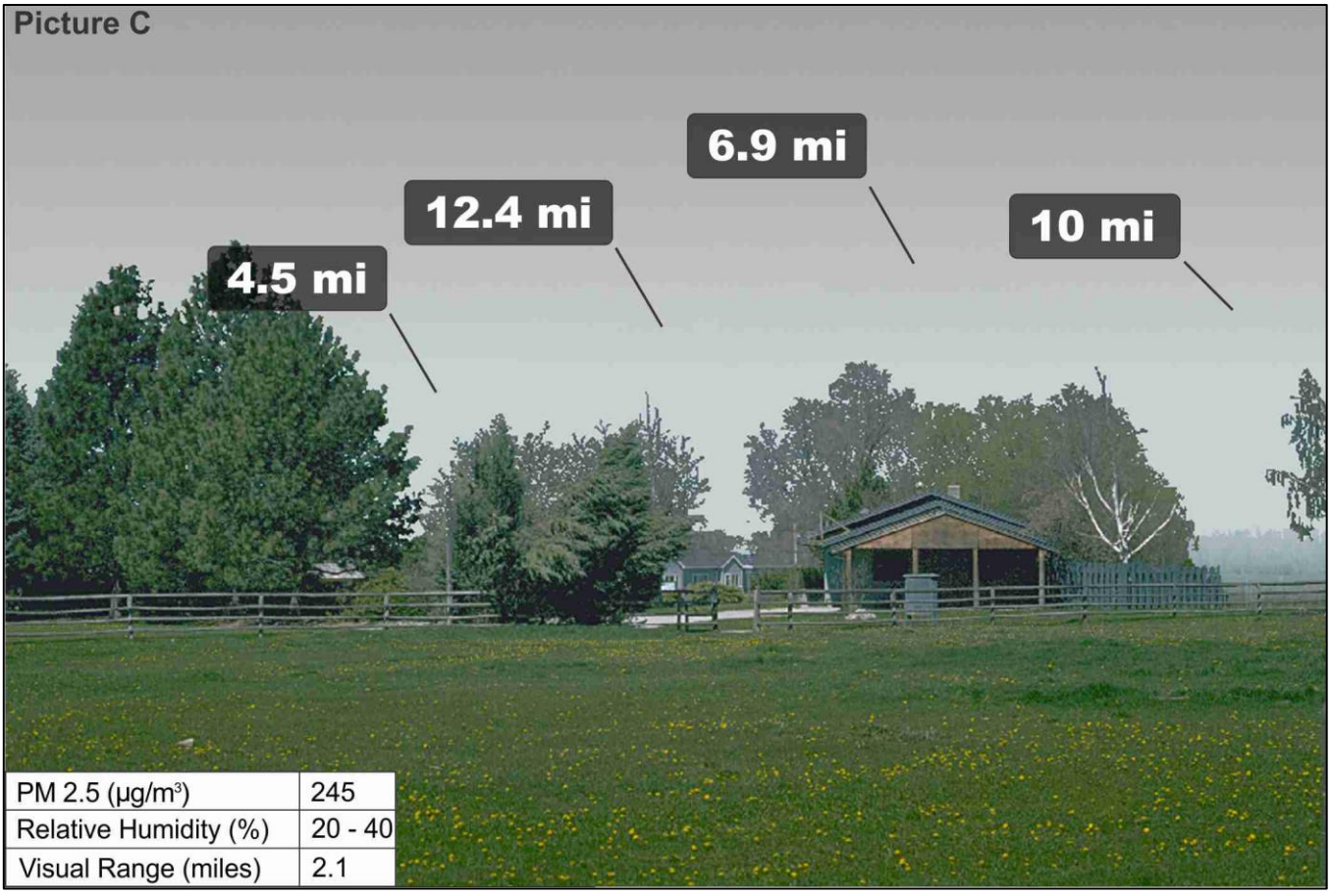


PM 2.5 (µg/m³)	< 5
Relative Humidity (%)	20
Visual Range (miles)	73.9

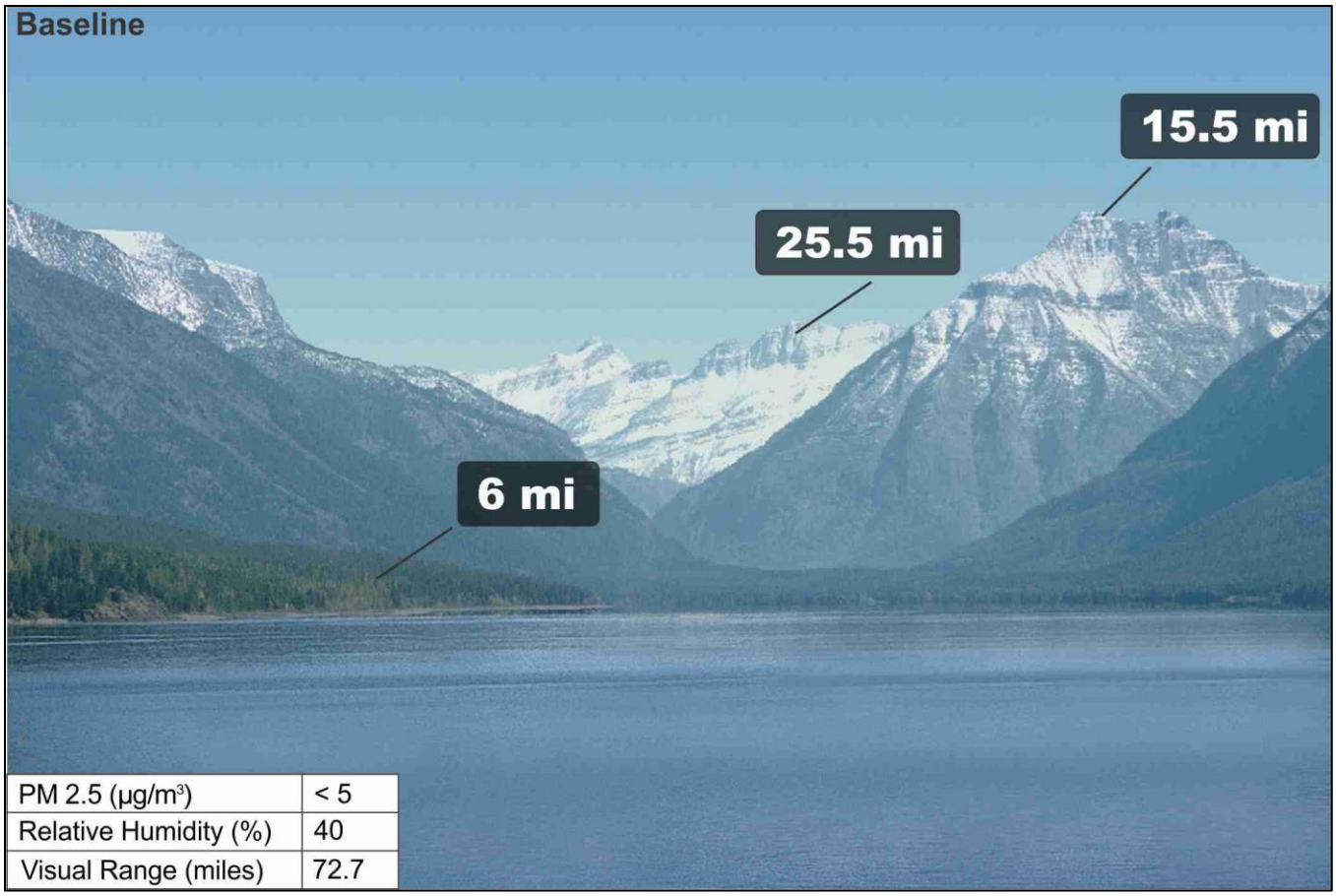


PM 2.5 (µg/m³)	19
Relative Humidity (%)	20
Visual Range (miles)	25.5

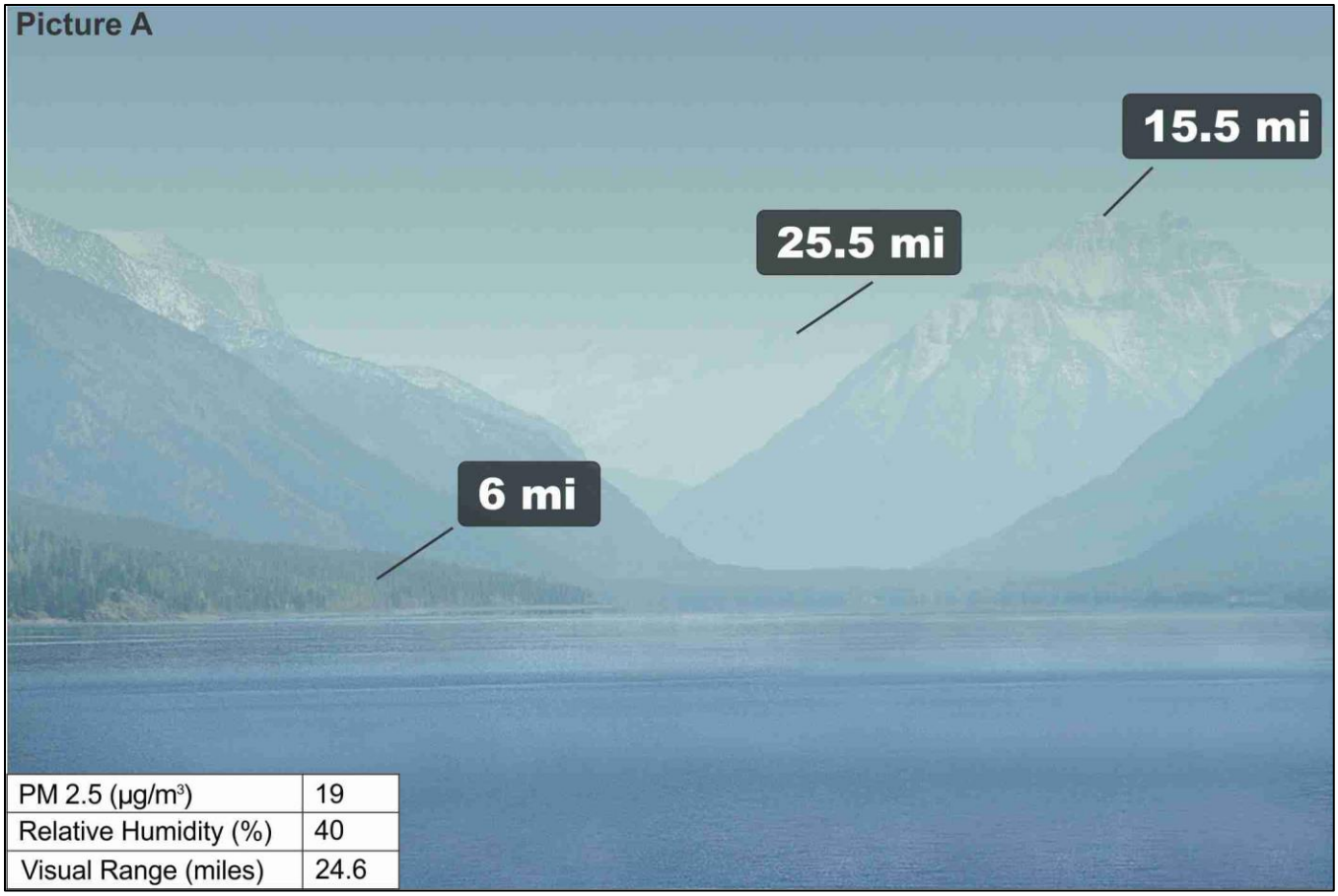

Picture B
6.9 mi
12.4 mi
10 mi
4.5 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 20
Visual Range (miles) 4.6


Picture C
6.9 mi
12.4 mi
10 mi
4.5 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 20 - 40
Visual Range (miles) 2.1

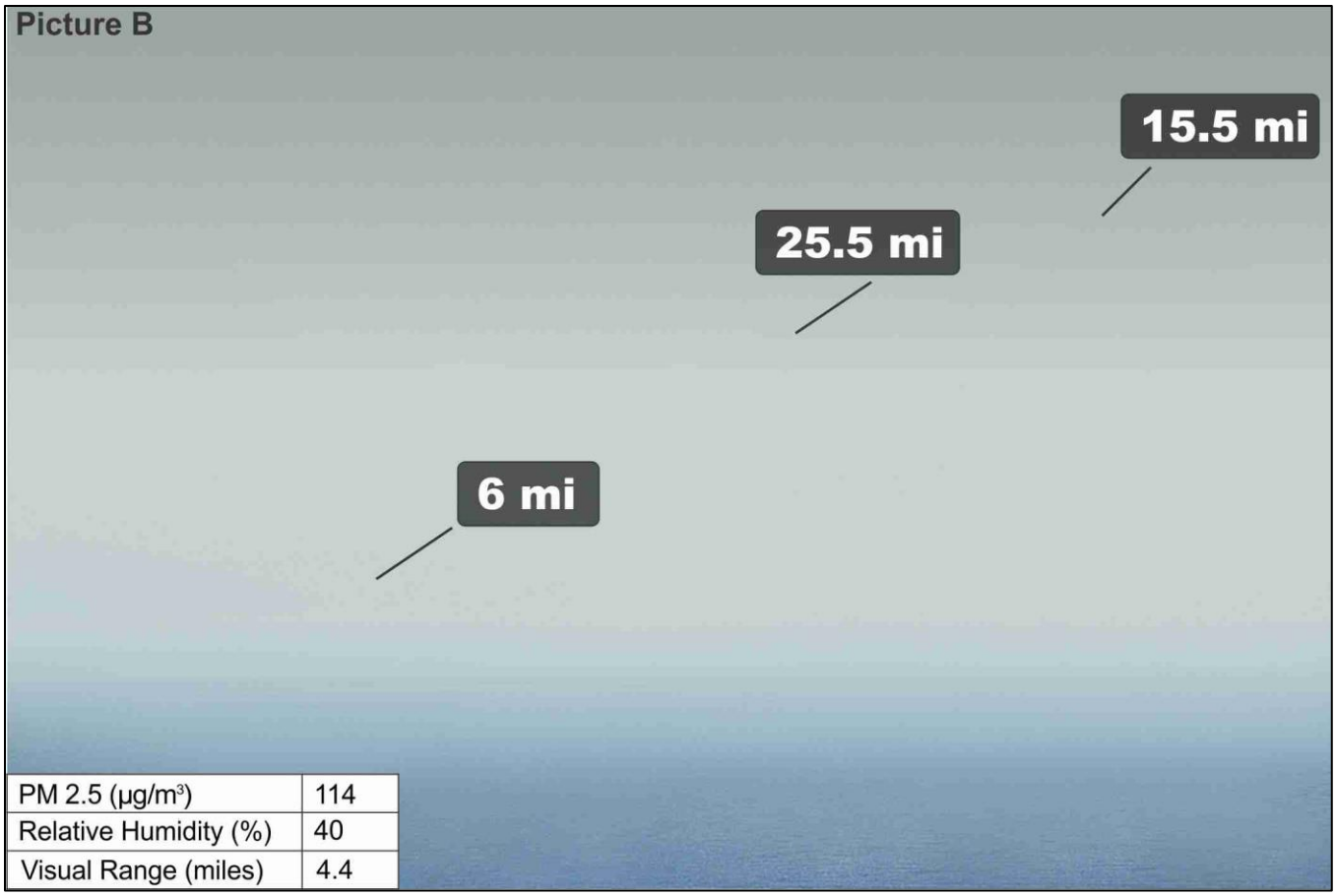
GLACIER NATIONAL PARK, MT



PM 2.5 (μg/m³)	< 5
Relative Humidity (%)	40
Visual Range (miles)	72.7



PM 2.5 (μg/m³)	19
Relative Humidity (%)	40
Visual Range (miles)	24.6


Picture B
15.5 mi
25.5 mi
6 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 40
Visual Range (miles) 4.4

U.S. Forest Service, Region 2 – Rocky Mountain National Park, CO

Particulate data from 794 days of sampling (September 1990 to May 1999) at Rocky Mountain National Park were chosen to represent baseline and elevated regional air quality concentrations (table 4). The baseline image represents an area free of smoke-impaired visibility (<5 μg · m^{-3} fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 μg · m^{-3}) and RH are noted (table 5) and illustrated for Rocky Mountain National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Rocky Mountain National Park (EPA 2014).

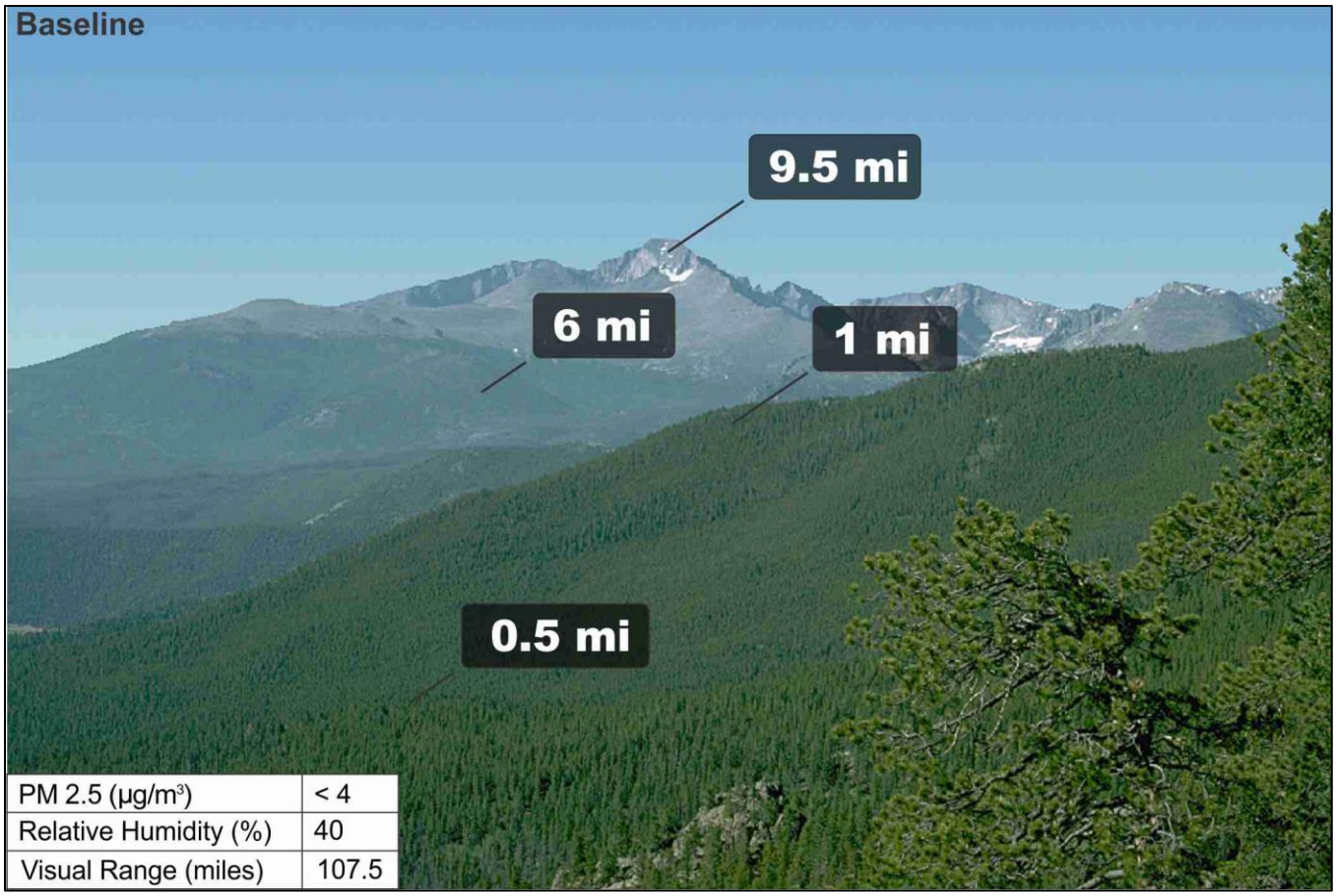
Table 4—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Rocky Mountain National Park, CO

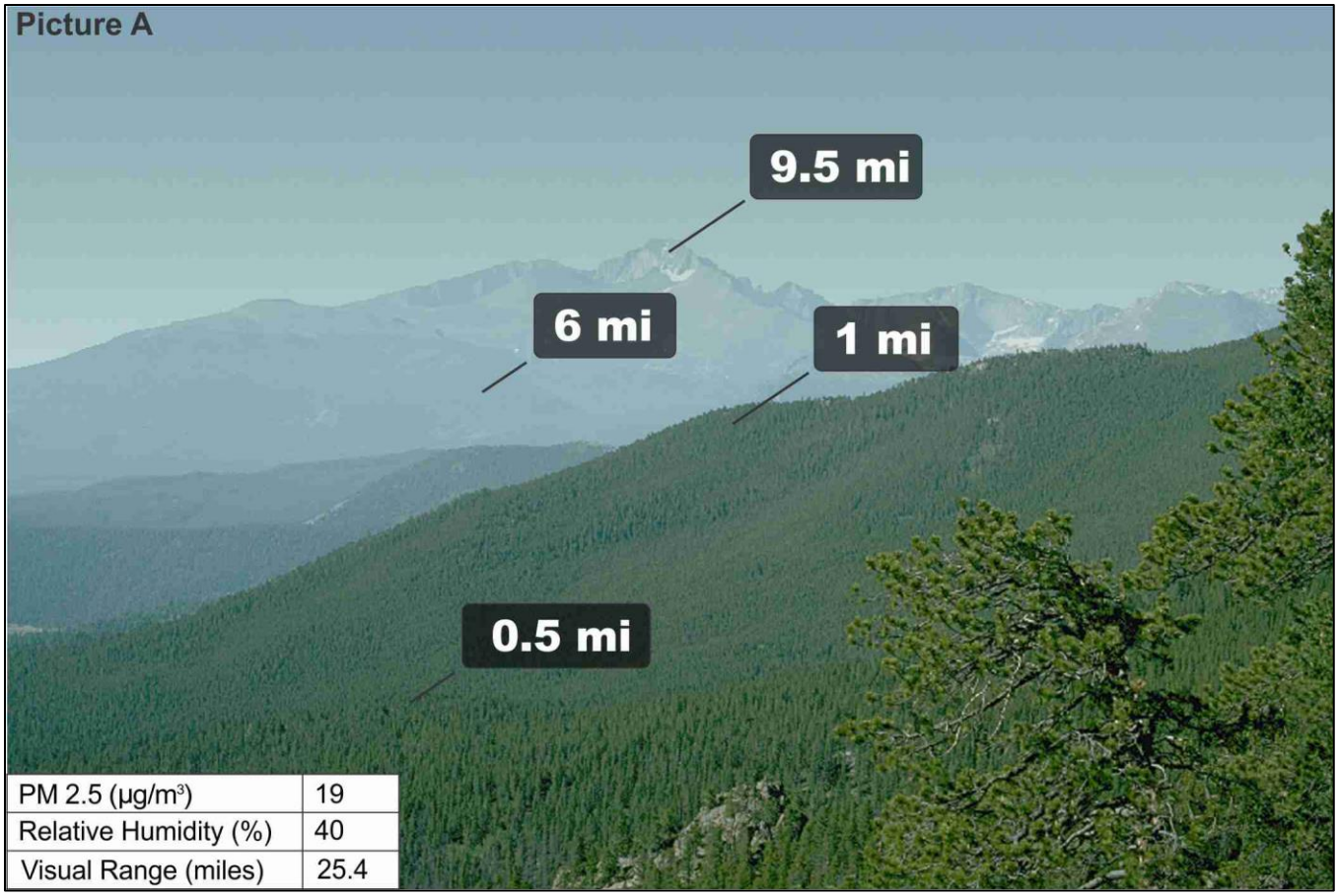
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- *μg · m*$^{-3}$ ----------			
Ammonium sulfate	0.93	1.49	1.49	1.49
Ammonium nitrate	0.29	0.50	0.50	0.50
Organic carbon	1.00	14.77	103.96	226.95
LAC/Black carbon	0.17	0.96	6.77	14.78
Fine soil	0.63	1.28	1.28	1.28
Coarse mass	3.96	5.88	11.40	24.50

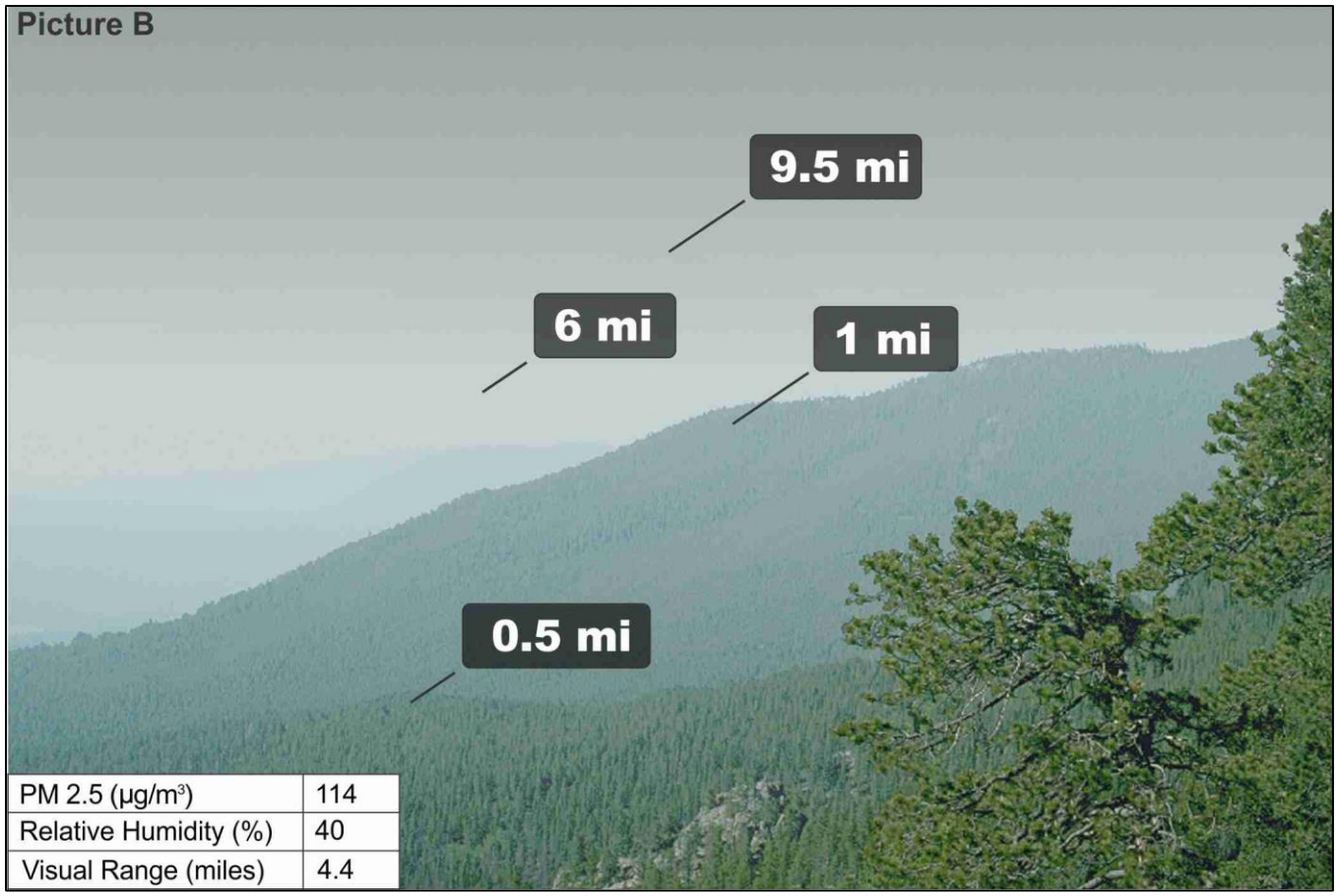
Table 5—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Rocky Mountain National Park, CO

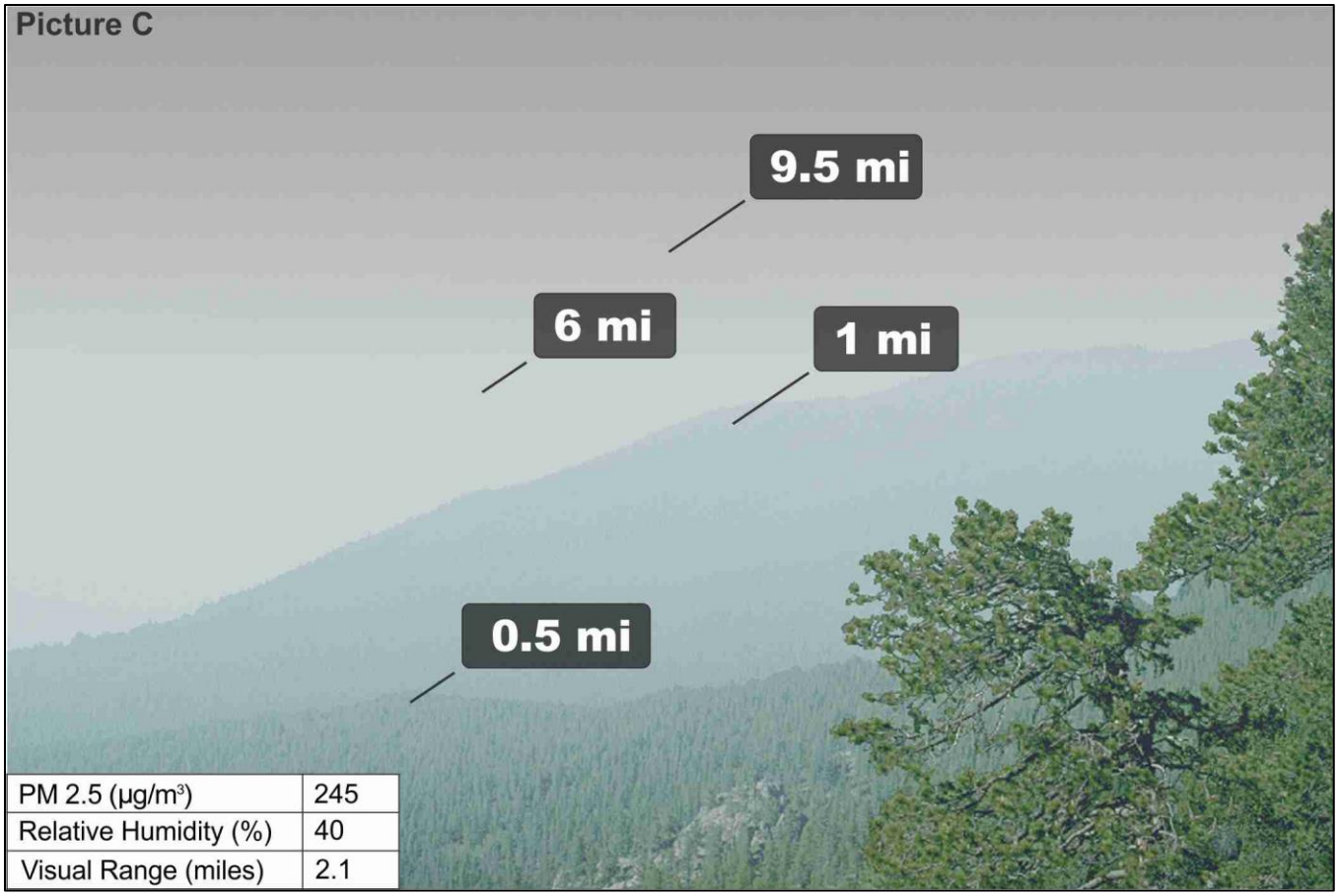
$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
μg · m^{-3}	*percent*	*miles*	*km*
<5 (baseline)	40	107.5	173.0
19 (picture A)	40	25.4	40.9
	50	24.6	39.6
	60	23.8	38.3
114 (picture B)	40	4.4	7.1
	50	4.3	7.0
	60	4.2	6.8
245 (picture C)	40	2.1	3.3
	50-60	2.0	3.2

ROCKY MOUNTAIN NATIONAL PARK, CO






Picture B
9.5 mi
6 mi
1 mi
0.5 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 40
Visual Range (miles) 4.4


Picture C
9.5 mi
6 mi
1 mi
0.5 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 40
Visual Range (miles) 2.1

U.S. Forest Service, Region 3 – Grand Canyon National Park, AZ

Particulate matter data from 857 days (March 1988 to August 1998) at Grand Canyon National Park were chosen to represent baseline and elevated regional air quality concentrations (table 6). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 7) and illustrated for Grand Canyon National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Grand Canyon National Park (EPA 2014).

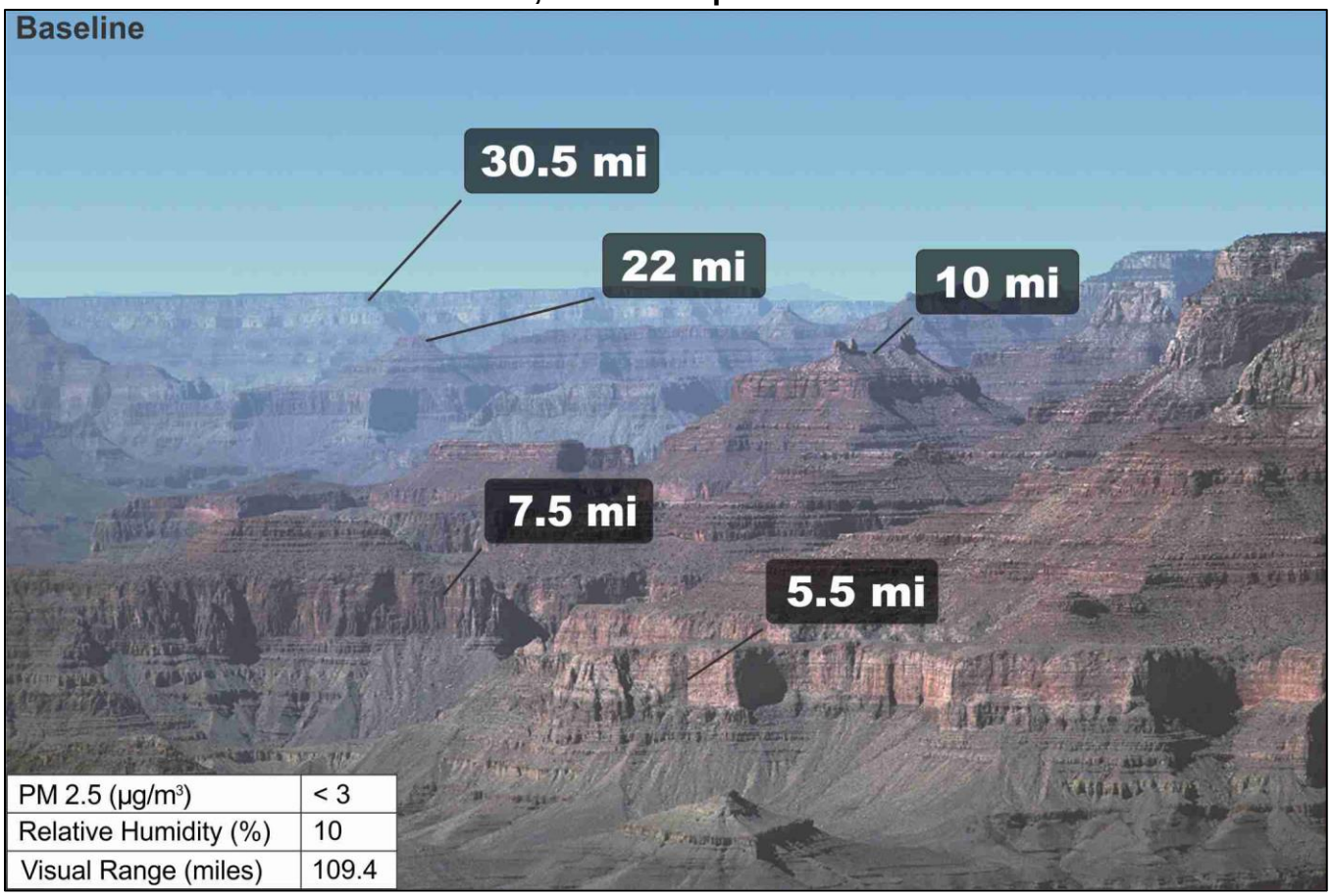
Table 6—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Grand Canyon National Park, AZ

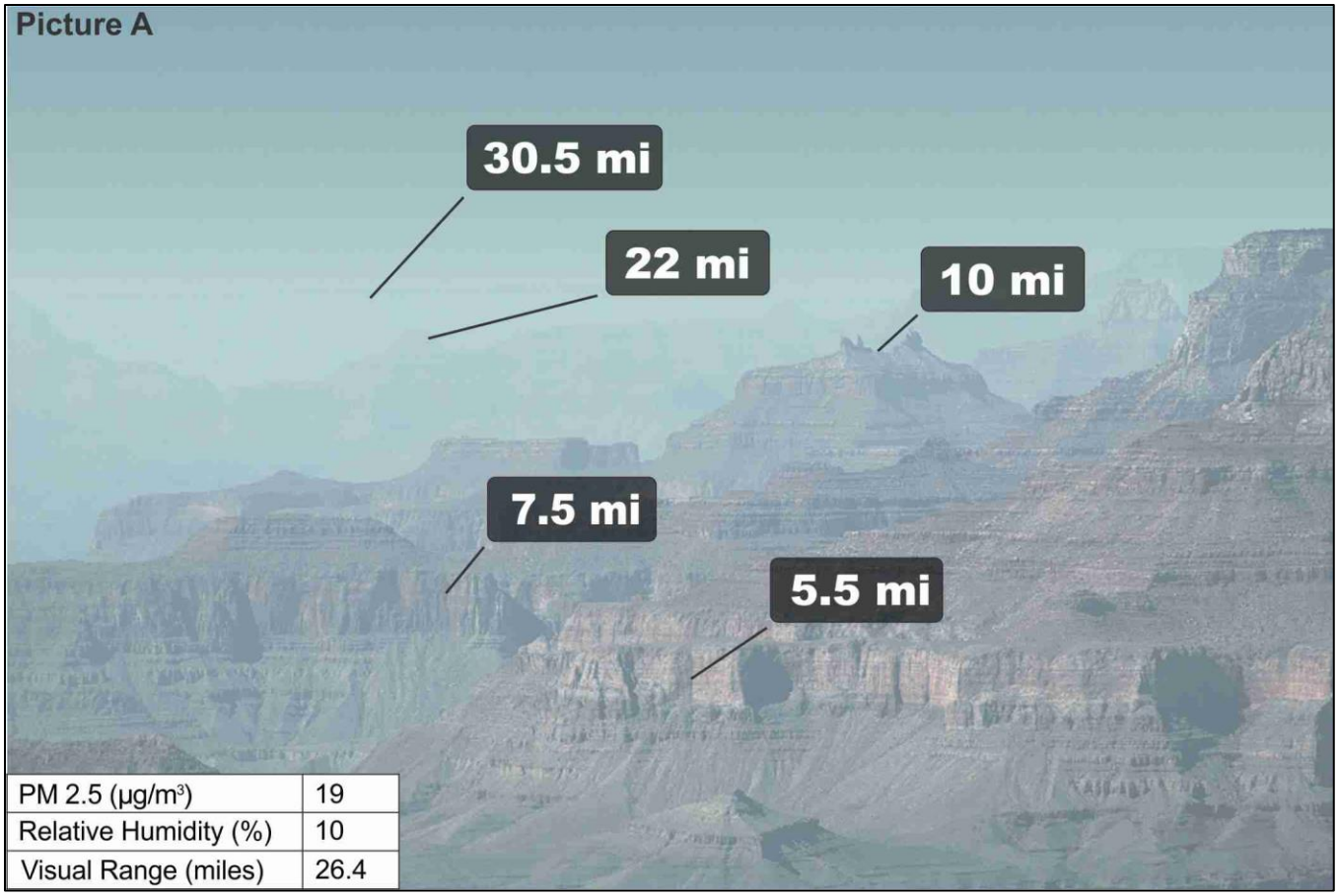
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	1.01	1.59	1.59	1.59
Ammonium nitrate	0.20	0.31	0.31	0.31
Organic carbon	0.80	14.90	104.09	227.08
LAC/Black carbon	0.18	0.97	6.78	14.79
Fine soil	0.61	1.23	1.23	1.23
Coarse mass	4.99	7.16	11.40	24.50

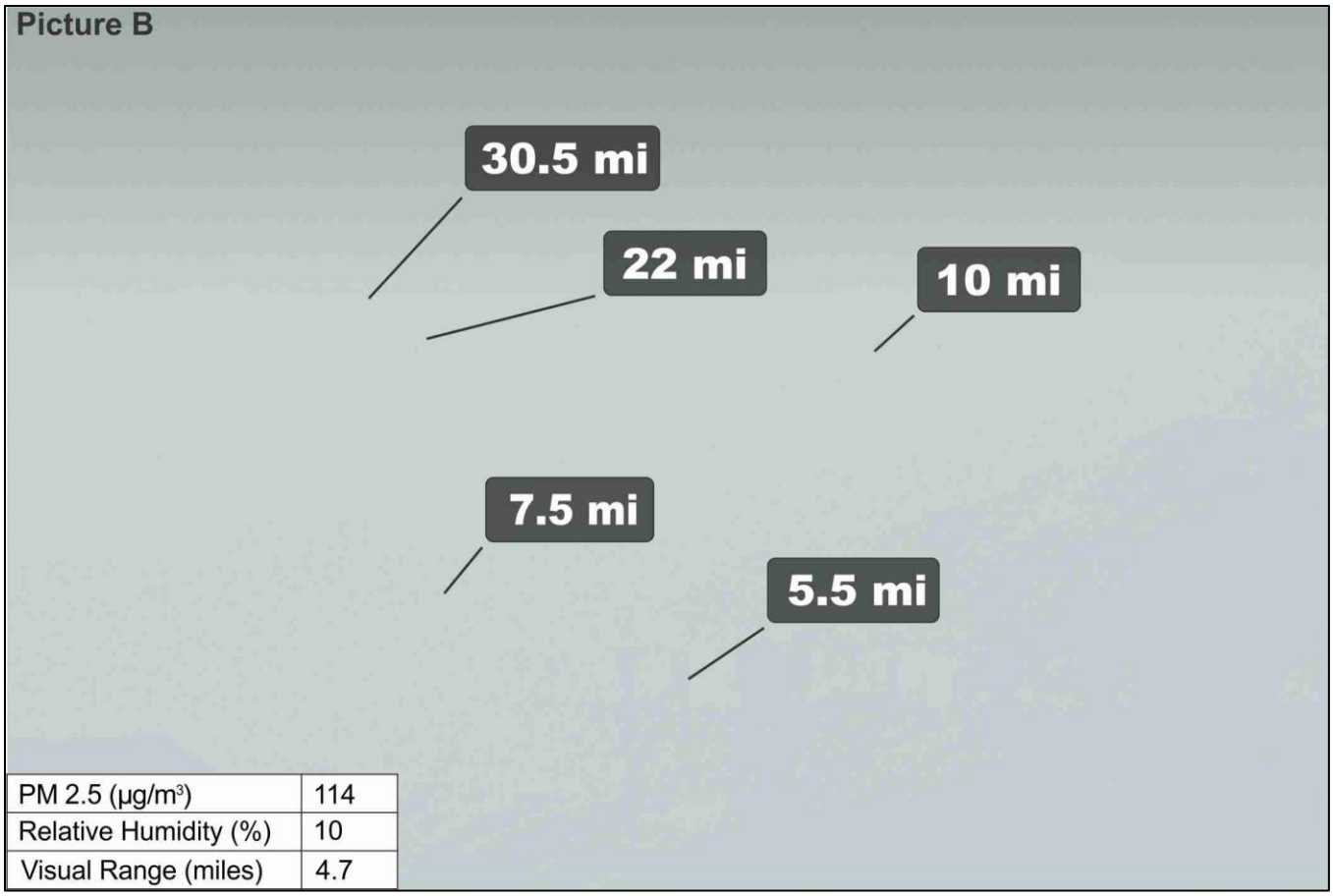
Table 7—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Grand Canyon National Park, AZ

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	10	109.4	176.0
19 (picture A)	10	26.4	42.5
	20	26.0	41.8
	30	25.6	41.2
	40	25.1	40.4
	50	24.4	39.2
	60	23.5	37.9
114 (picture B)	10	4.7	7.6
	20	4.6	7.4
	30	4.5	7.3
	40	4.4	7.1
	50	4.3	7.0
	60	4.2	6.8
245 (picture C)	10	2.2	3.5
	20-40	2.1	3.4
	50	2.0	3.2
	60	1.9	3.1

GRAND CANYON NATIONAL PARK, AZ – Example 1

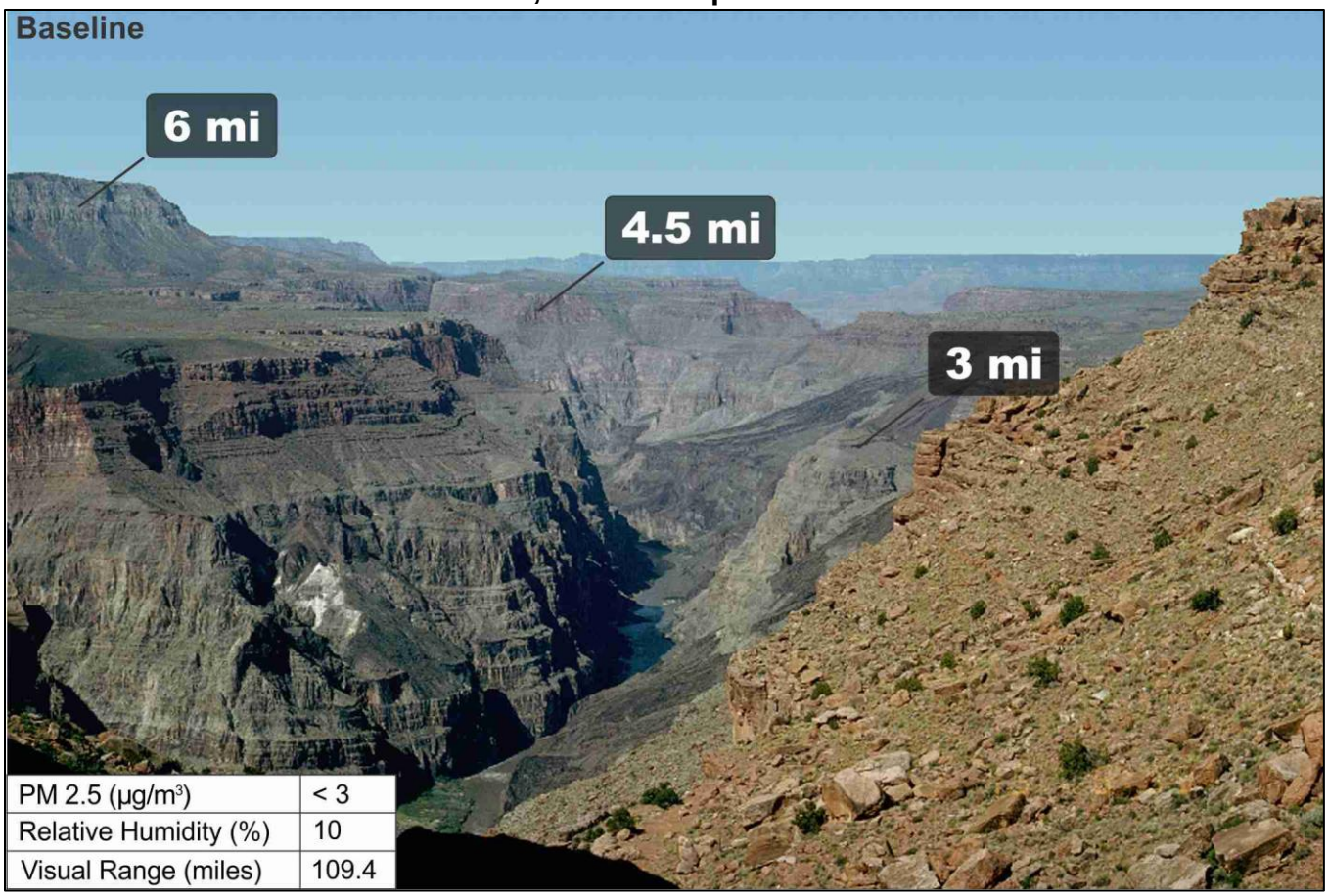


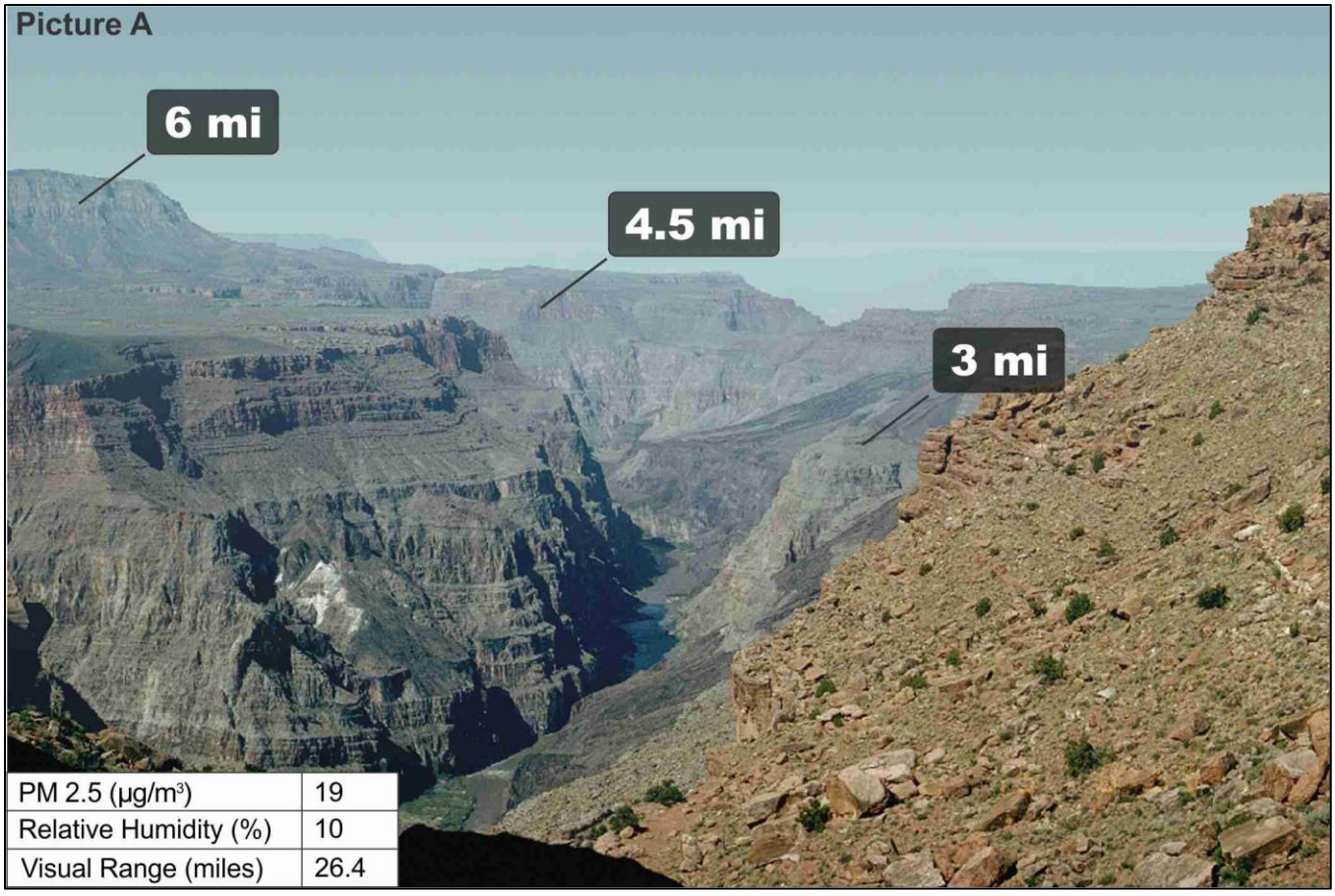


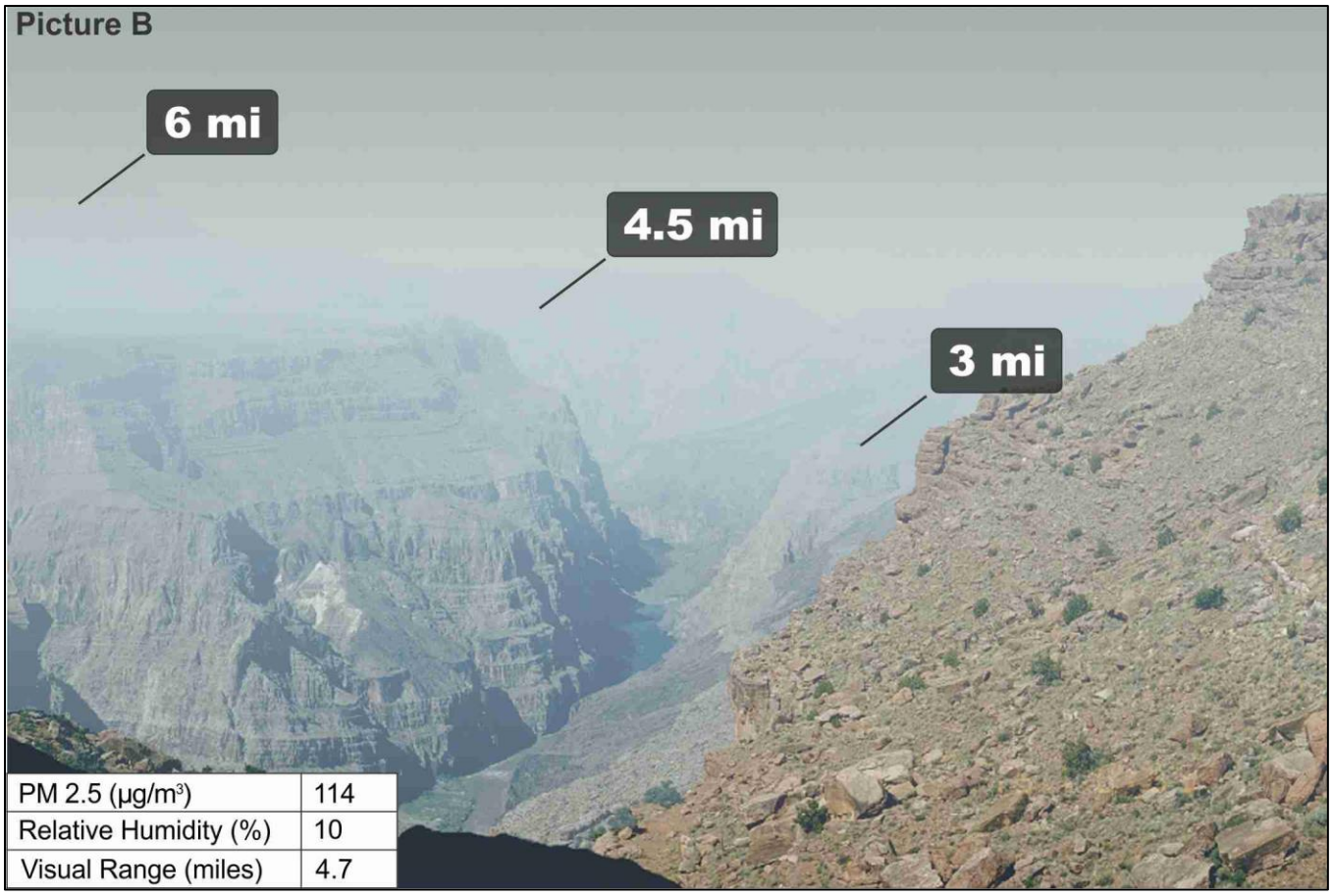


PM 2.5 (µg/m³)	114
Relative Humidity (%)	10
Visual Range (miles)	4.7

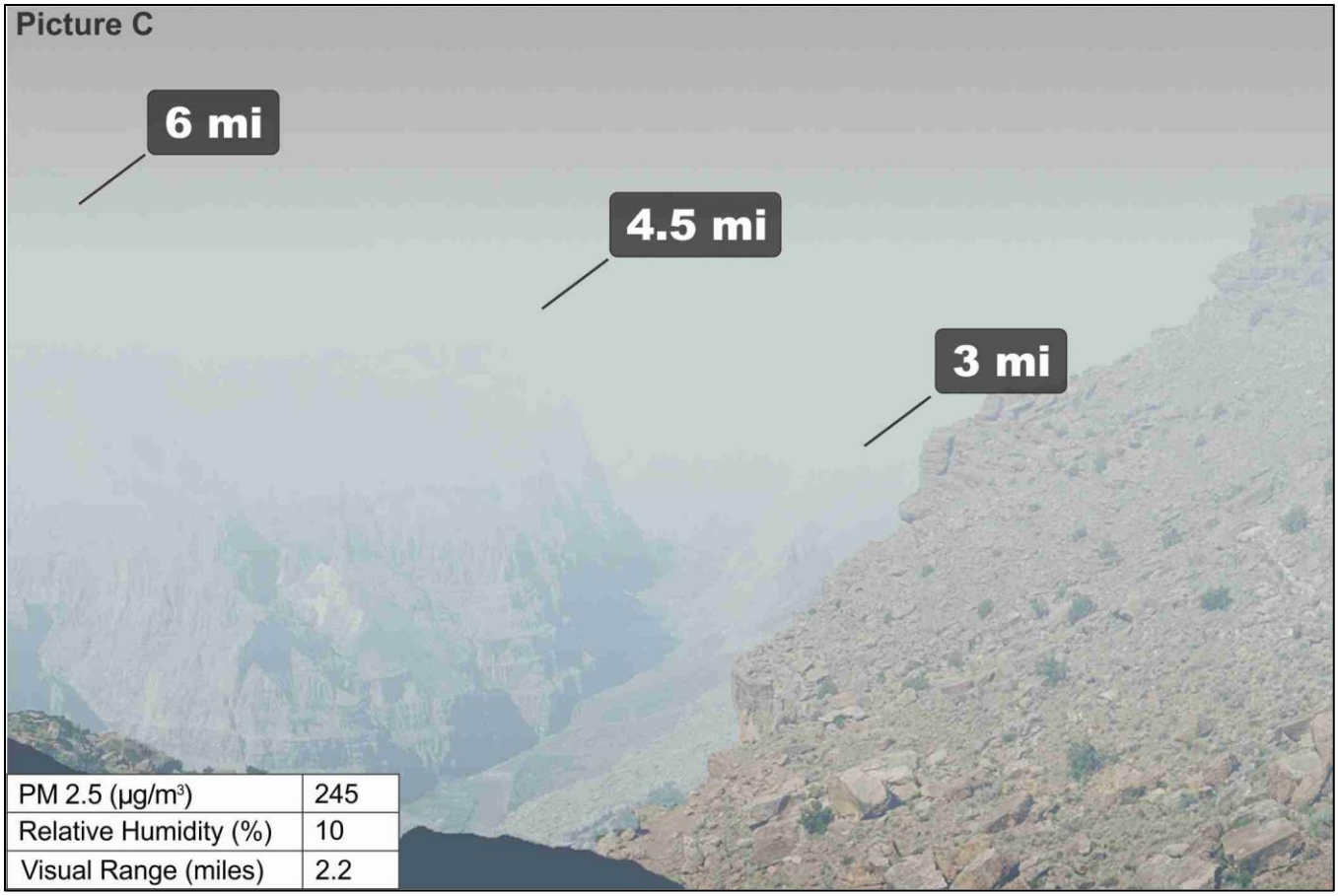
GRAND CANYON NATIONAL PARK, AZ – Example 2







PM 2.5 (µg/m³)	114
Relative Humidity (%)	10
Visual Range (miles)	4.7



PM 2.5 (µg/m³)	245
Relative Humidity (%)	10
Visual Range (miles)	2.2

U.S. Forest Service, Region 4 – Canyonlands National Park, UT

Particulate data from 964 days (March 1988 to May 1999) at Canyonlands National Park were chosen to represent baseline and elevated regional air quality concentrations (table 8). The baseline image represents an area free of smoke-impaired visibility (<5 μg · m^{-3} fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 μg · m^{-3}) and RH are noted (table 9) and illustrated for Canyonlands National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Canyonlands National Park (EPA 2014).

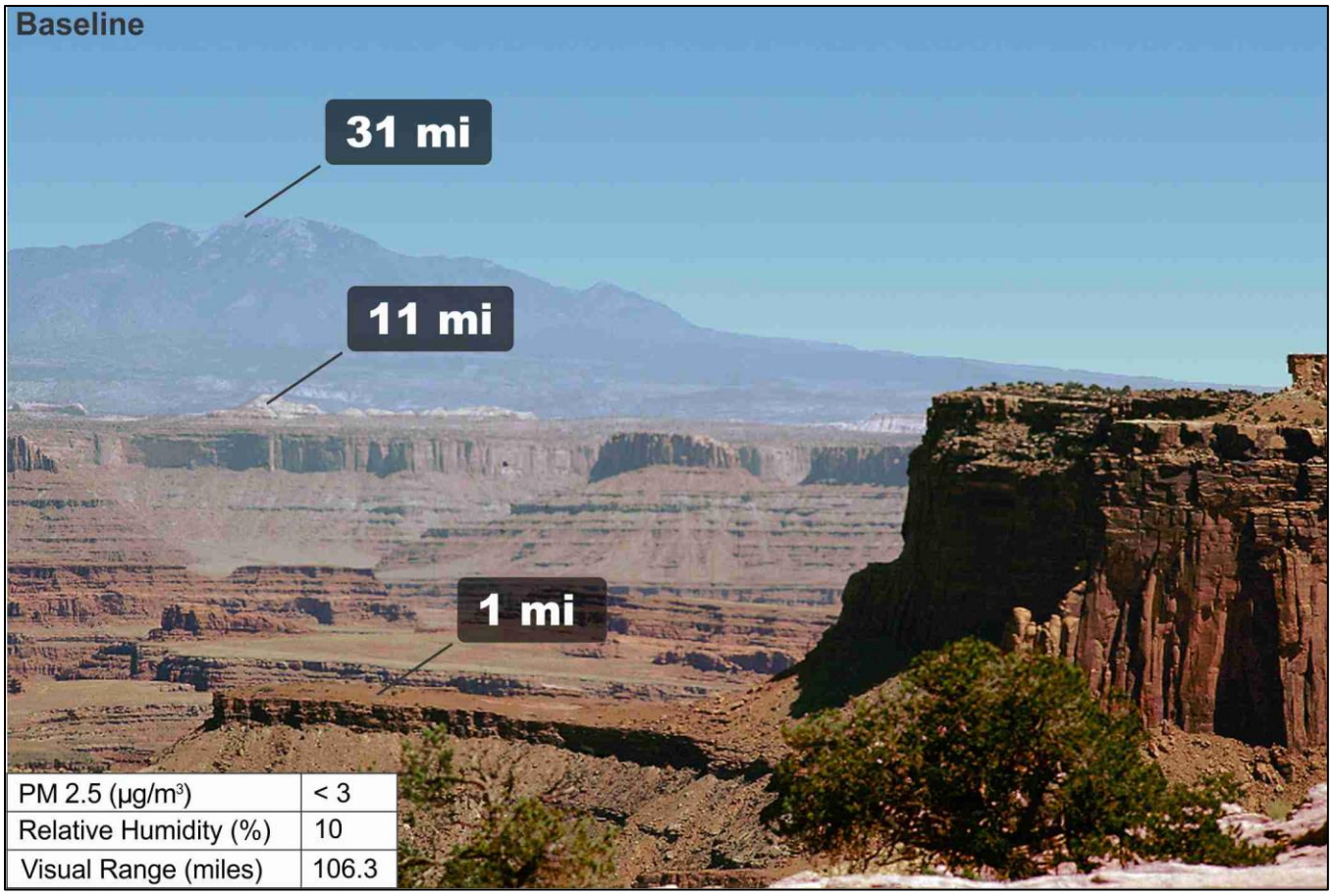
Table 8—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Canyonlands National Park, UT

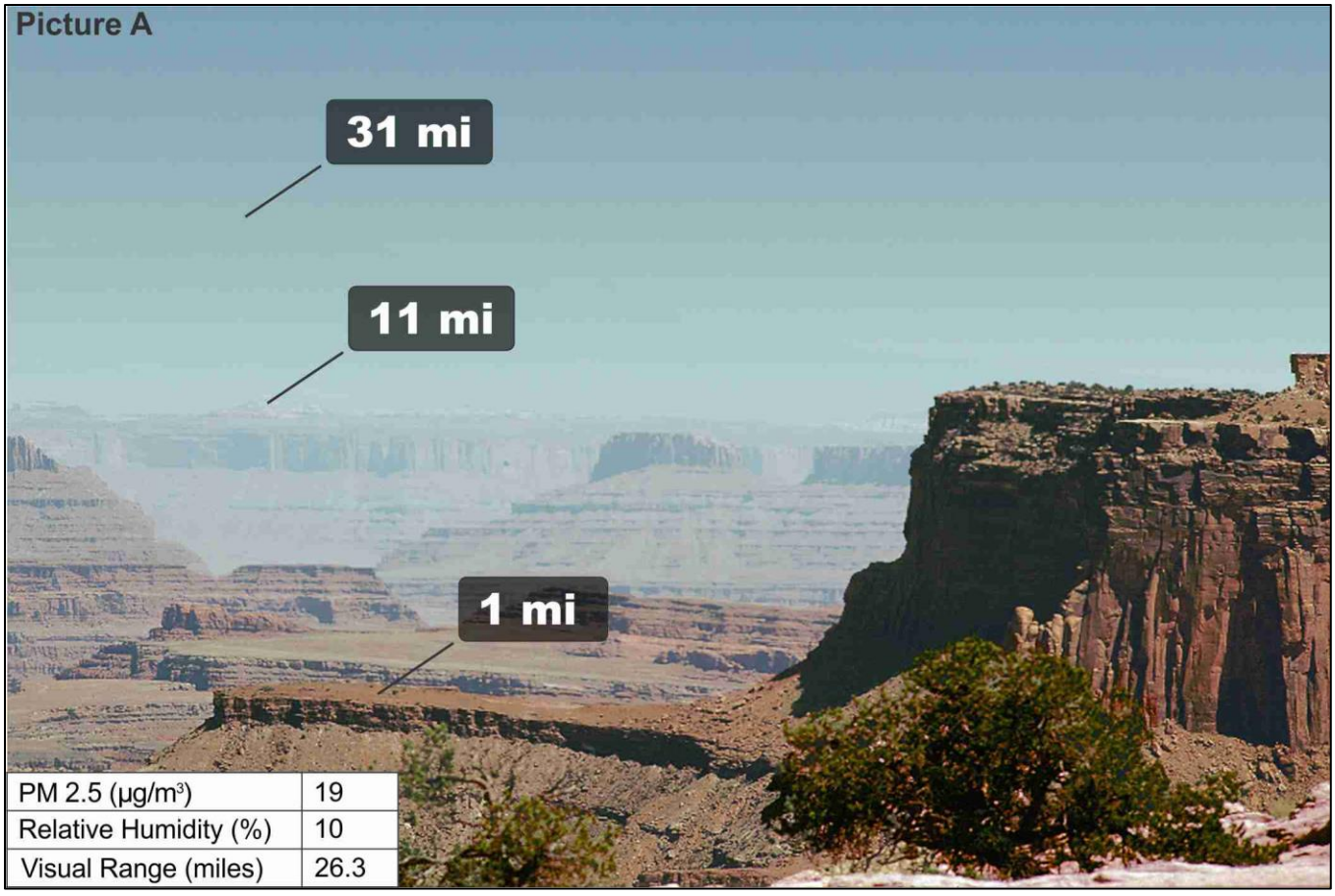
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- *μg · m^{-3}* ----------			
Ammonium sulfate	1.08	1.54	1.54	1.54
Ammonium nitrate	0.23	0.37	0.37	0.37
Organic carbon	0.82	14.77	103.96	226.95
LAC/Black carbon	0.16	0.96	6.77	14.78
Fine soil	0.69	1.36	1.36	1.36
Coarse mass	5.60	8.43	11.40	24.50

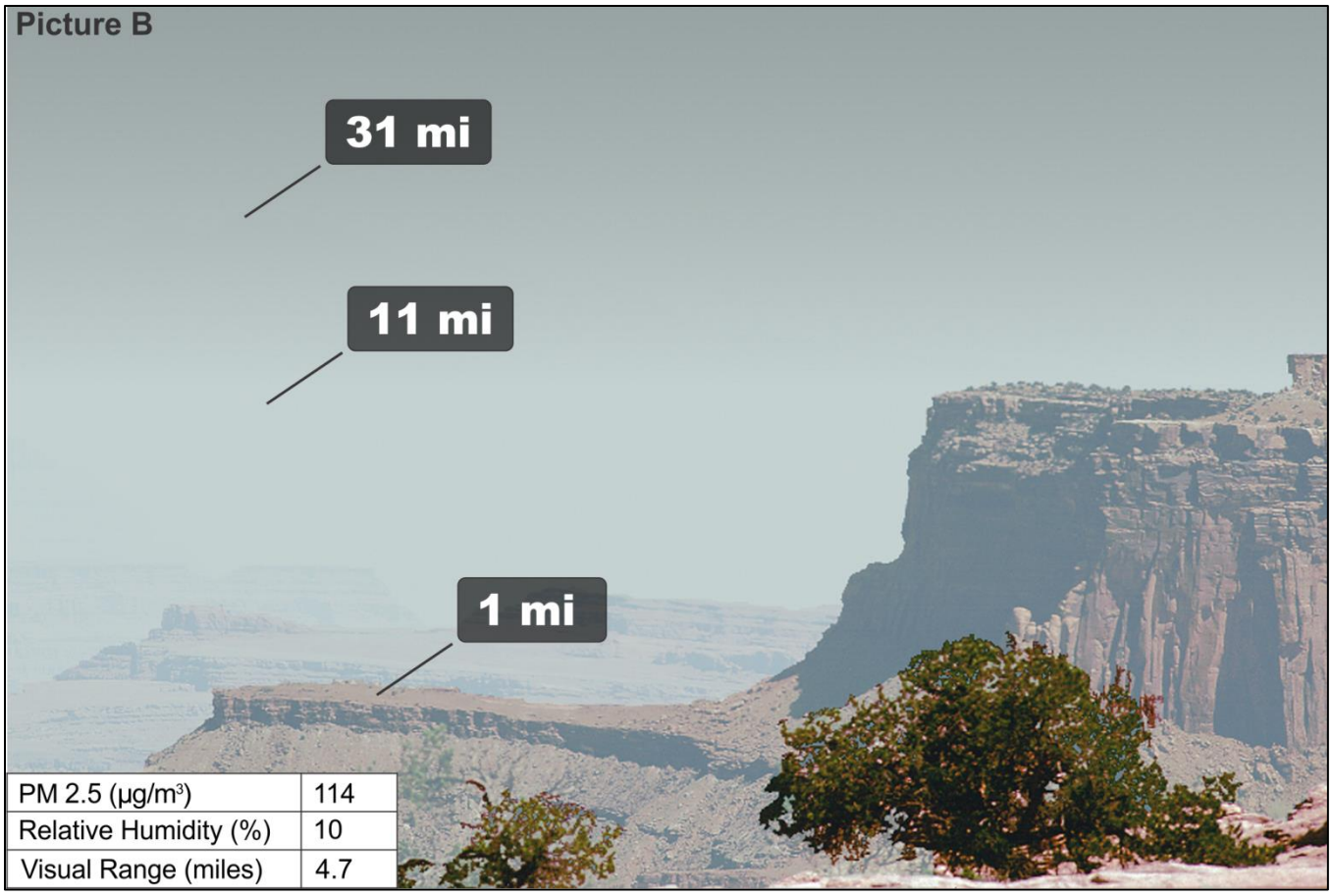
Table 9—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Canyonlands National Park, UT

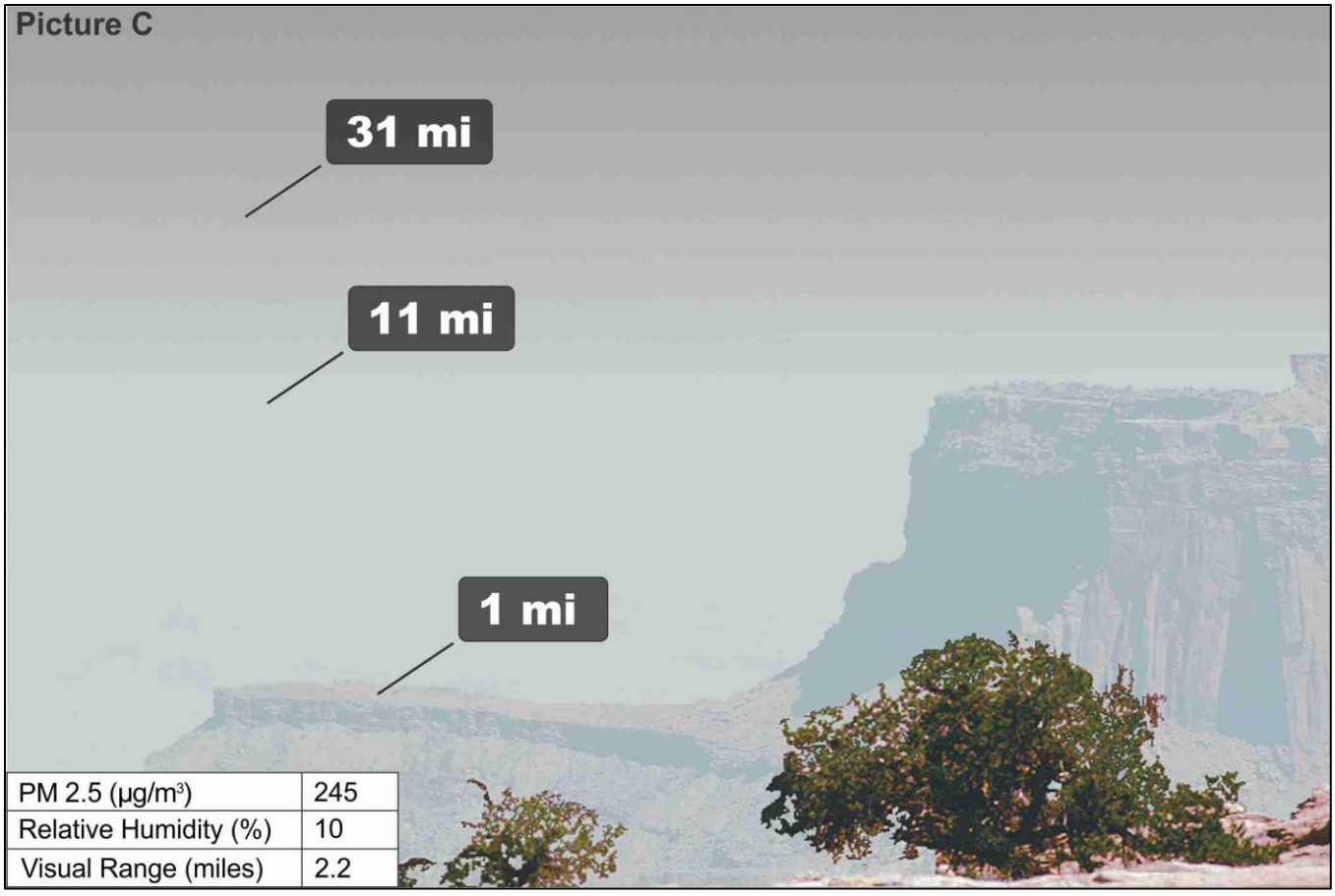
$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
μg · m^{-3}	*percent*	*miles*	*km*
<5 (baseline)	10	106.3	171.0
19 (picture A)	10	26.3	42.4
	20	26.0	41.8
	30	25.5	41.1
	40	25.0	40.3
114 (picture B)	10	4.7	7.6
	20	4.6	7.4
	30	4.5	7.3
	40	4.4	7.1
245 (picture C)	10	2.2	3.5
	20-40	2.1	3.4

CANYONLANDS NATIONAL PARK, UT






Picture B
31 mi
11 mi
1 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 10
Visual Range (miles) 4.7


Picture C
31 mi
11 mi
1 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 10
Visual Range (miles) 2.2

U.S. Forest Service, Region 4 – Great Basin National Park, NV

Particulate data from 681 days of sampling (May 1992 to May 1999) at Great Basin National Park were chosen to represent baseline and elevated regional air quality concentrations (table 10). The baseline image represents an area free of smoke-impaired visibility (<5 μg · m^{-3} fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 μg · m^{-3}) and RH are noted (table 11) and illustrated for Great Basin National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Great Basin National Park (EPA 2014).

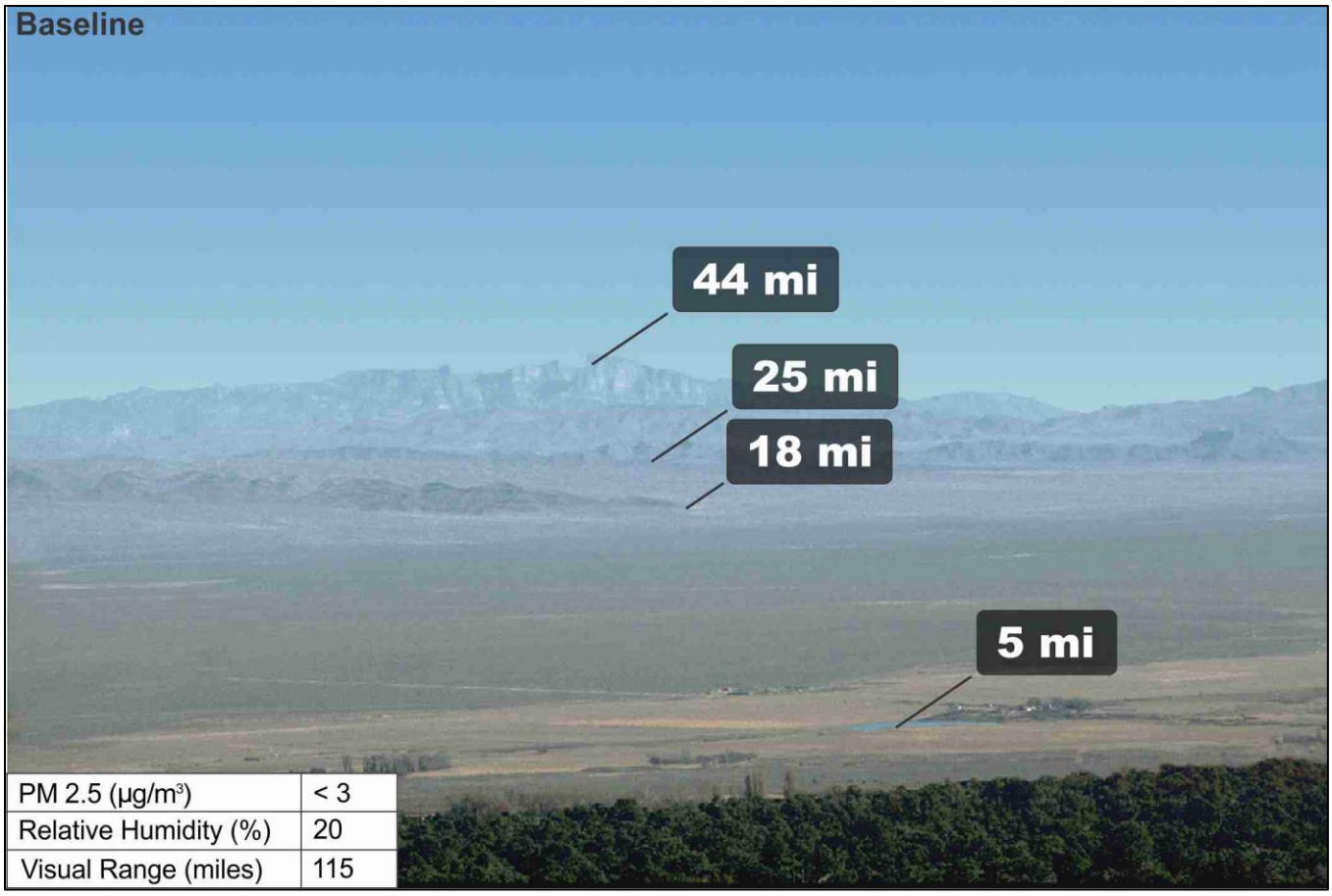
Table 10—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Great Basin National Park, NV

Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	0.68	1.13	1.13	1.13
Ammonium nitrate	0.16	0.31	0.31	0.31
Organic carbon	0.98	15.18	104.37	227.37
LAC/Black carbon	0.19	0.99	6.80	14.81
Fine soil	0.60	1.39	1.39	1.39
Coarse mass	3.73	5.50	11.40	24.50

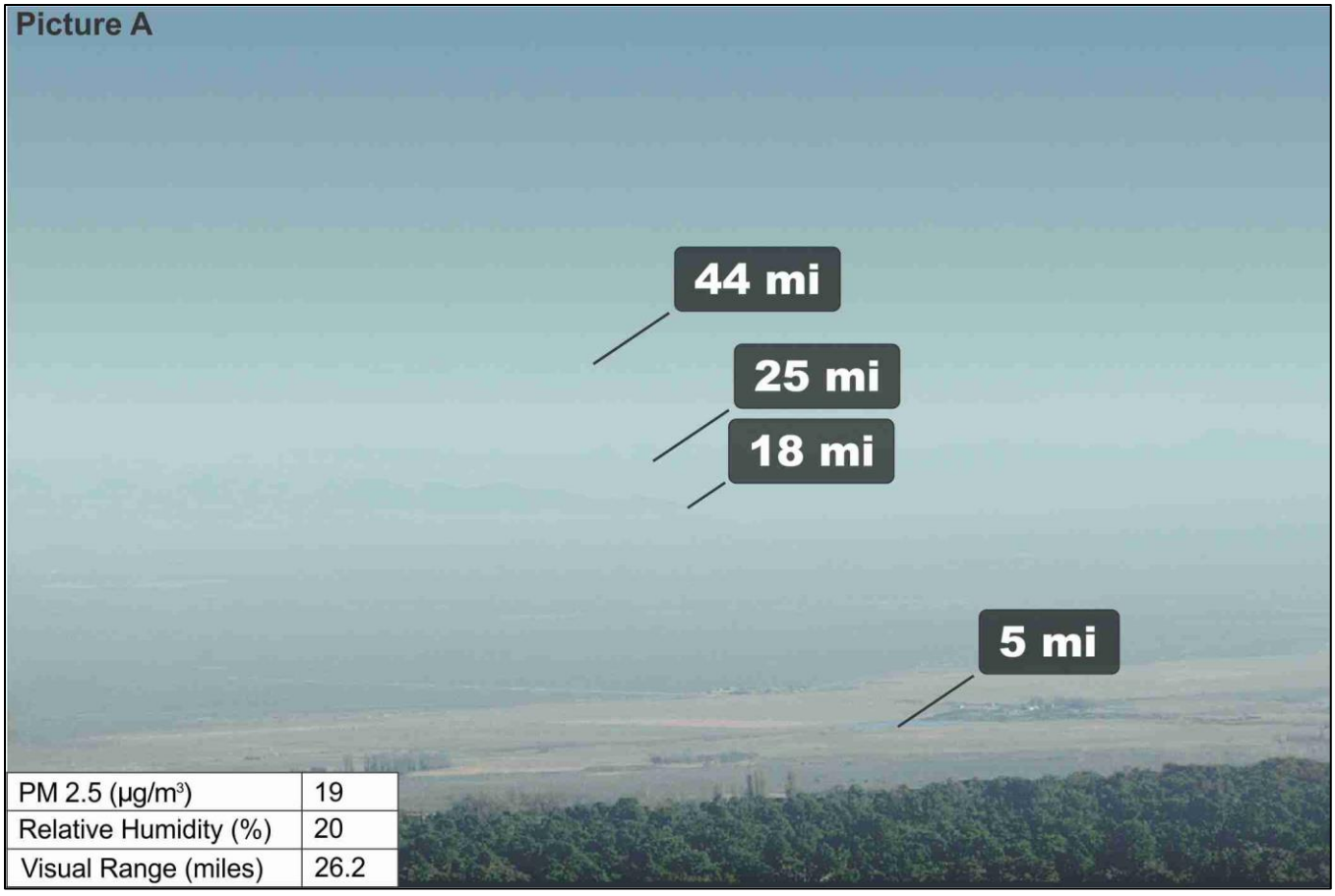
Table 11—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Great Basin National Park, NV

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	20	115.0	185.0
19 (picture A)	20	26.2	42.2
	30	25.8	41.6
	40	25.4	40.8
	50	24.7	39.7
114 (picture B)	20	4.6	7.4
	30	4.5	7.3
	40	4.4	7.1
	50	4.3	7.0
245 (picture C)	20-40	2.1	3.4
	50	2.0	3.3

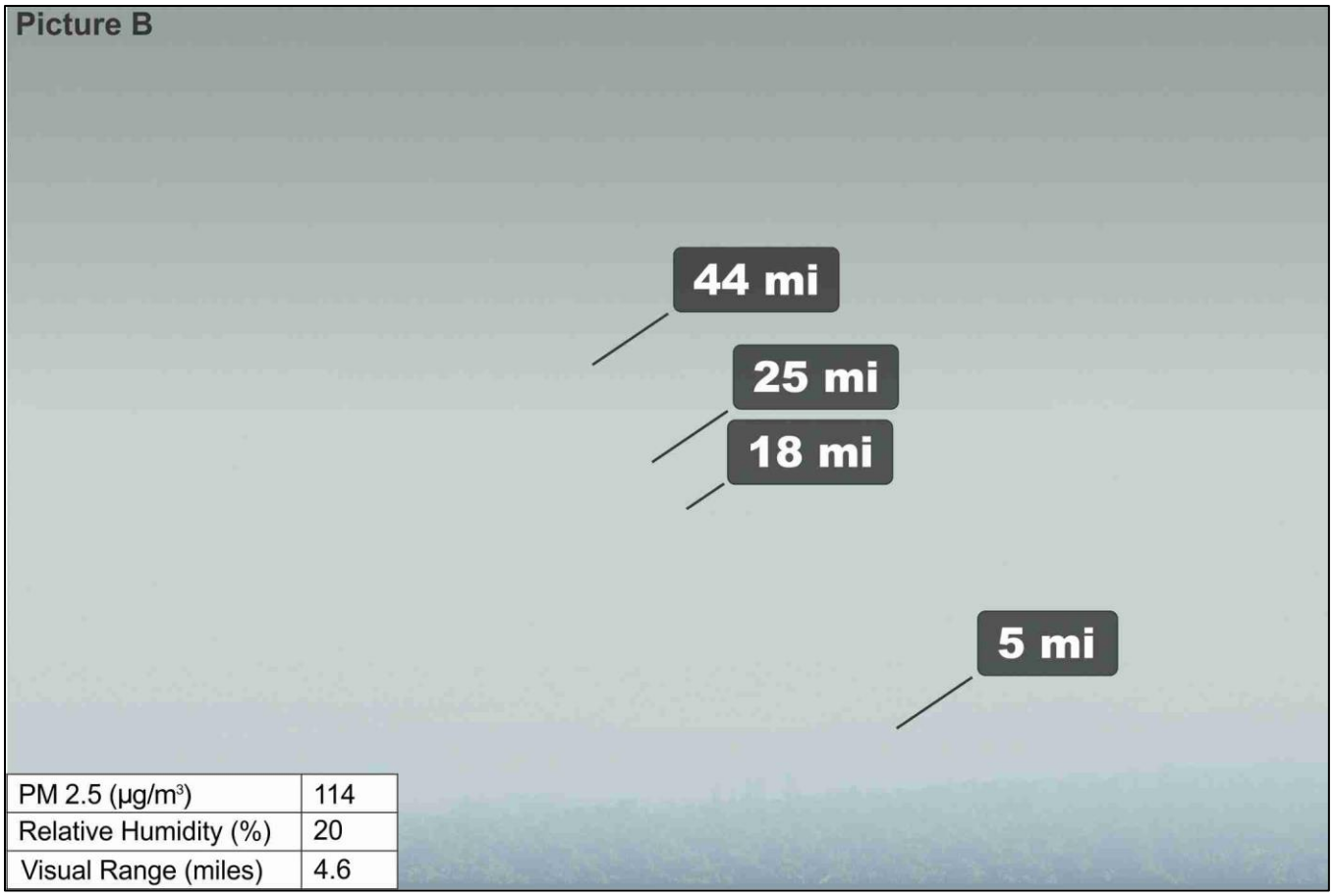
GREAT BASIN NATIONAL PARK, NV



PM 2.5 (µg/m³)	< 3
Relative Humidity (%)	20
Visual Range (miles)	115



PM 2.5 (µg/m³)	19
Relative Humidity (%)	20
Visual Range (miles)	26.2


Picture B
44 mi
25 mi
18 mi
5 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 20
Visual Range (miles) 4.6

U.S. Forest Service, Region 5 – Yosemite National Park, CA

Particulate data from 951 days (March 1988 to May 1999) at Yosemite National Park were chosen to represent baseline and elevated regional air quality concentrations (table 12). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 13) and illustrated for Yosemite National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Yosemite National Park (EPA 2014).

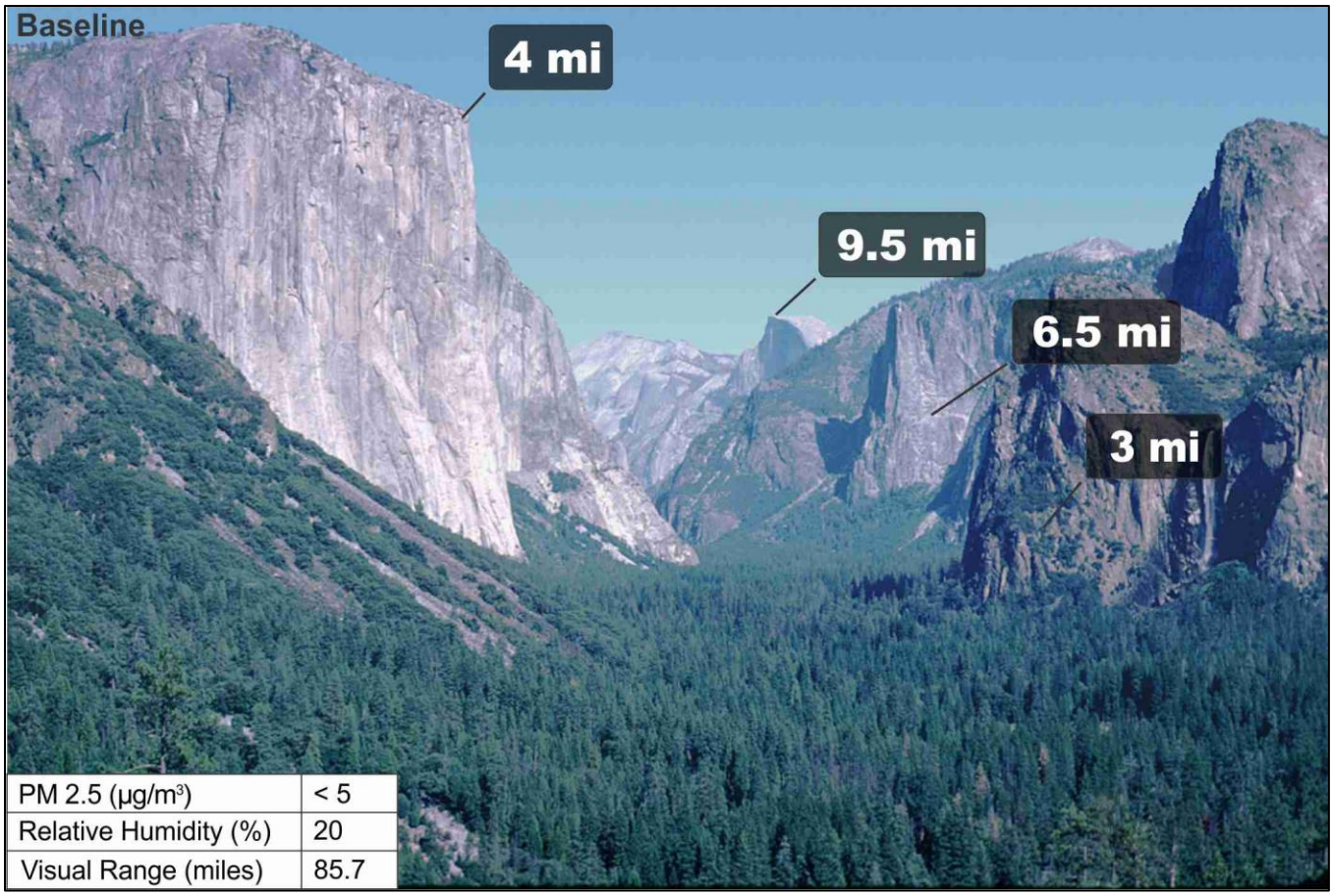
Table 12—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Yosemite National Park

Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	0.99	1.90	1.90	1.90
Ammonium nitrate	0.47	0.94	0.94	0.94
Organic carbon	1.94	14.20	103.39	226.38
LAC/Black carbon	0.27	0.92	6.73	14.74
Fine soil	0.56	1.04	1.04	1.04
Coarse mass	4.78	7.64	11.40	24.50

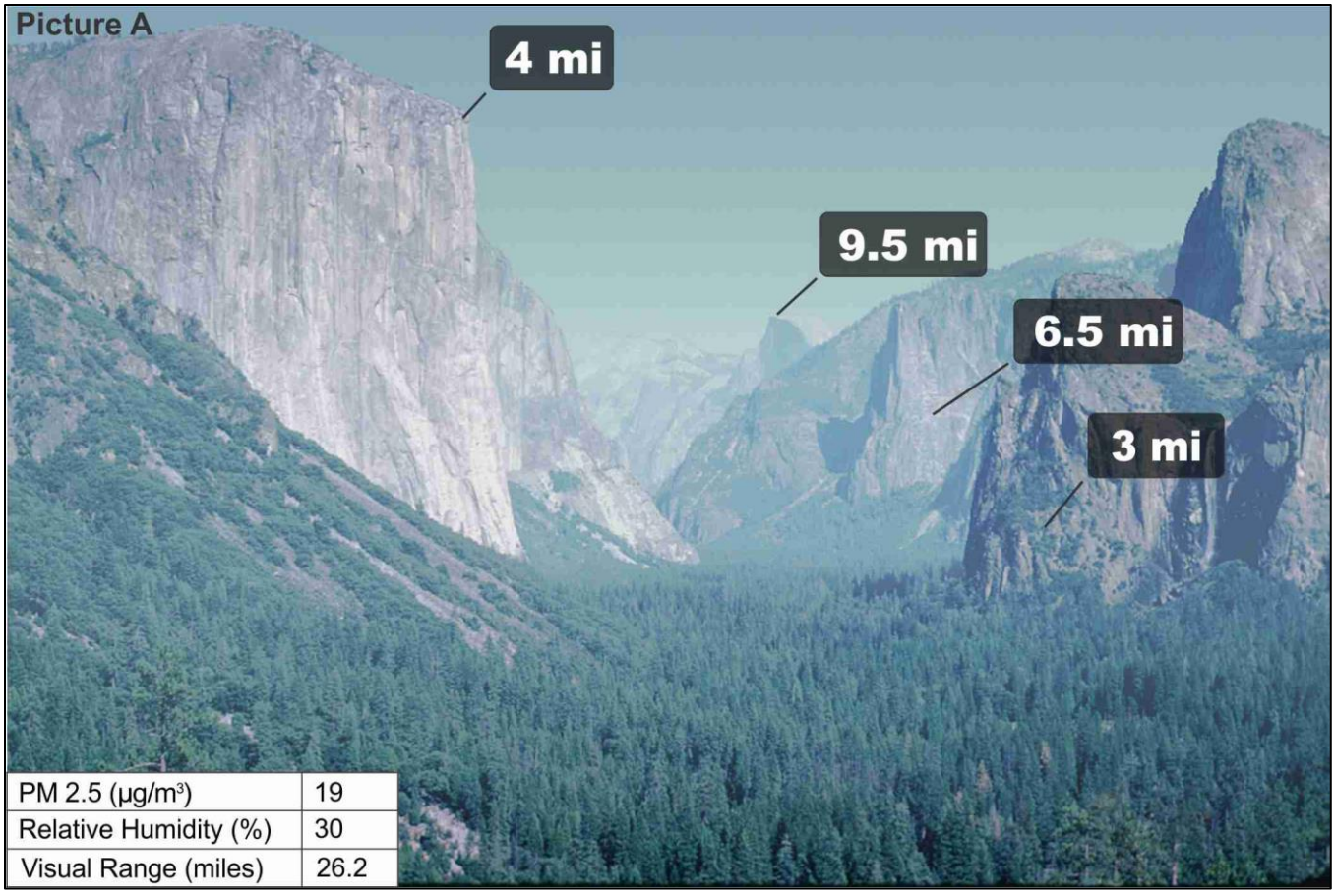
Table 13—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Yosemite National Park

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	20	85.7	138.0
19 (picture A)	20	26.2	42.1
	30	25.8	41.5
	40	25.2	40.6
	50	24.4	39.2
114 (picture B)	20	4.6	7.4
	30	4.5	7.3
	40	4.4	7.1
	50	4.3	7.0
245 (picture C)	20-40	2.1	3.4
	50	2.0	3.2

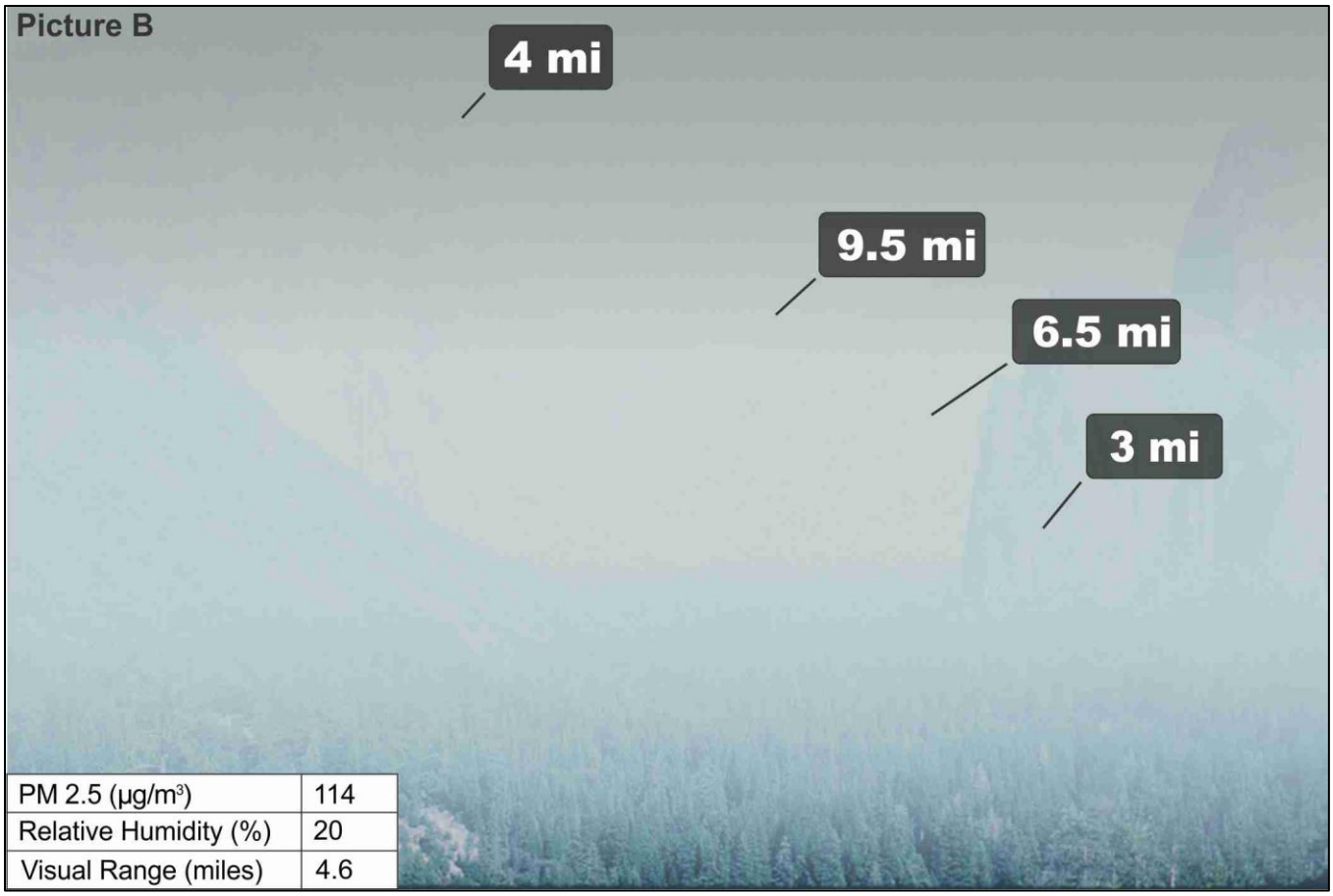
YOSEMITE NATIONAL PARK, CA



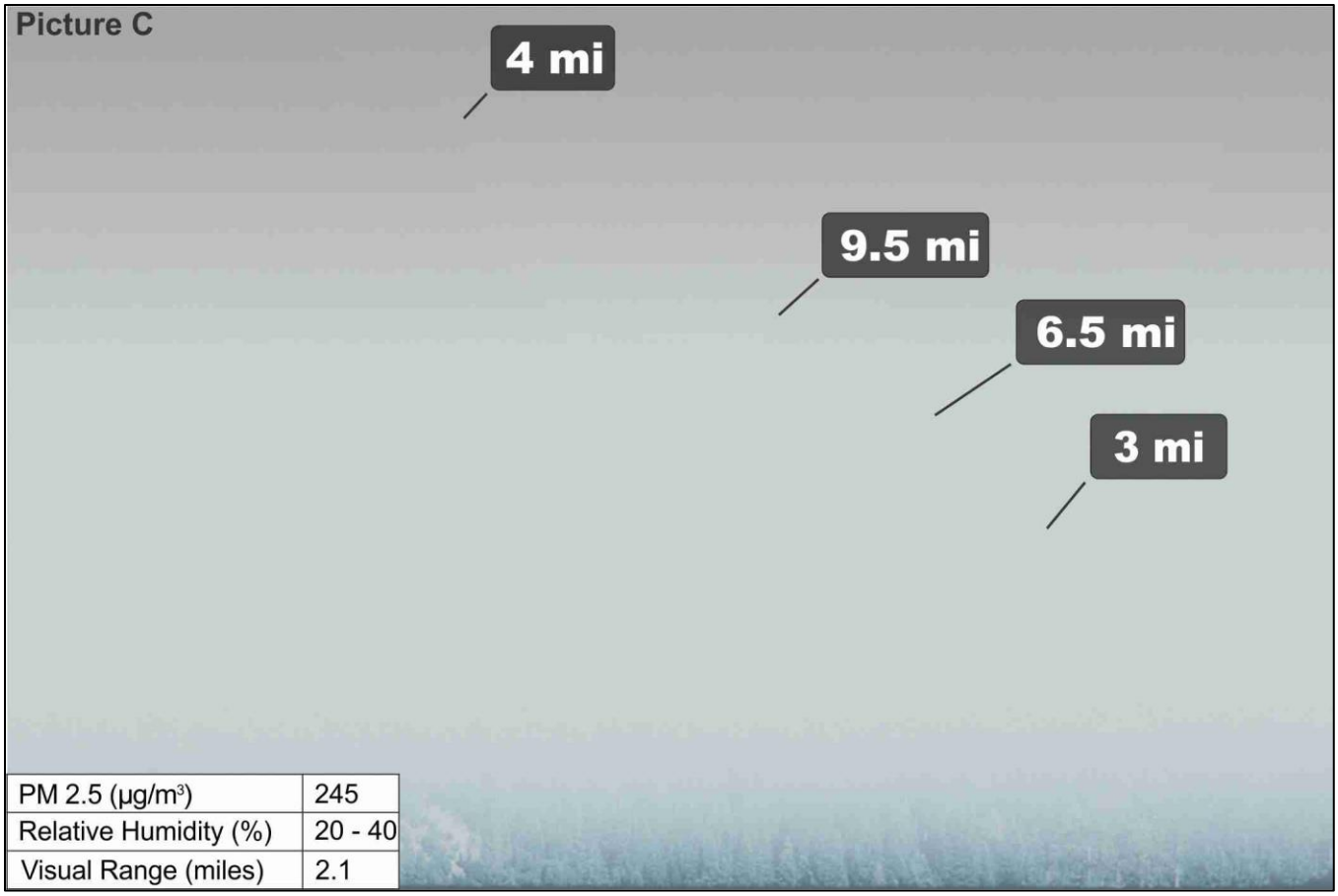
PM 2.5 (µg/m³)	< 5
Relative Humidity (%)	20
Visual Range (miles)	85.7



PM 2.5 (µg/m³)	19
Relative Humidity (%)	30
Visual Range (miles)	26.2



PM 2.5 (µg/m³)	114
Relative Humidity (%)	20
Visual Range (miles)	4.6



PM 2.5 (µg/m³)	245
Relative Humidity (%)	20 - 40
Visual Range (miles)	2.1

U.S. Forest Service, Region 6 – Columbia River Gorge, OR

Particulate data from 551 days of sampling (July 1993 to May 1999) in the Columbia River Gorge were chosen to represent baseline and elevated regional air quality concentrations (table 14). The baseline image represents an area free of smoke-impaired visibility (<5 μg · m^{-3} fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 μg · m^{-3}) and RH are noted (table 15) and illustrated for the Columbia River Gorge on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Portland, OR (NOAA 2014).

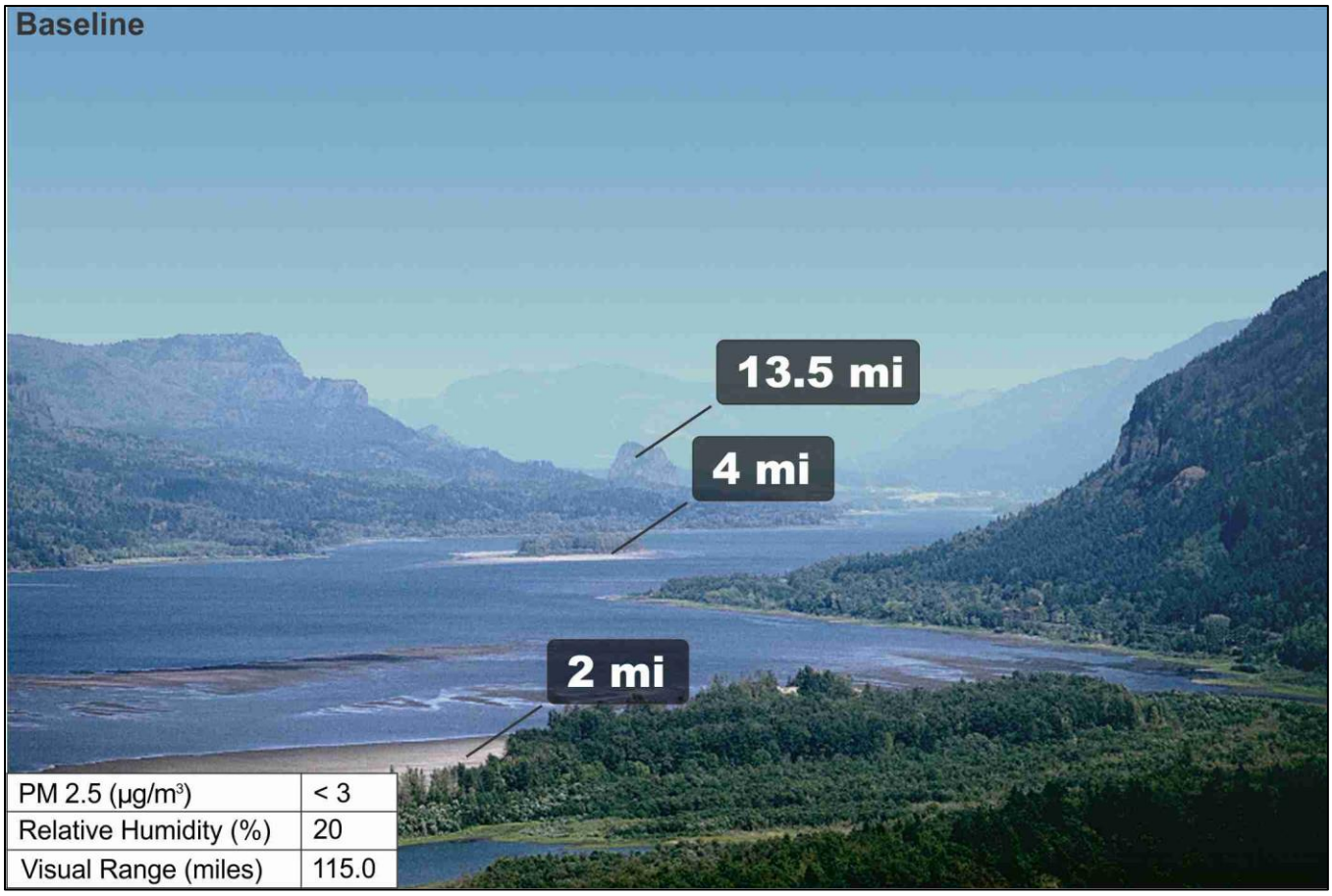
Table 14—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in the Columbia River Gorge, OR

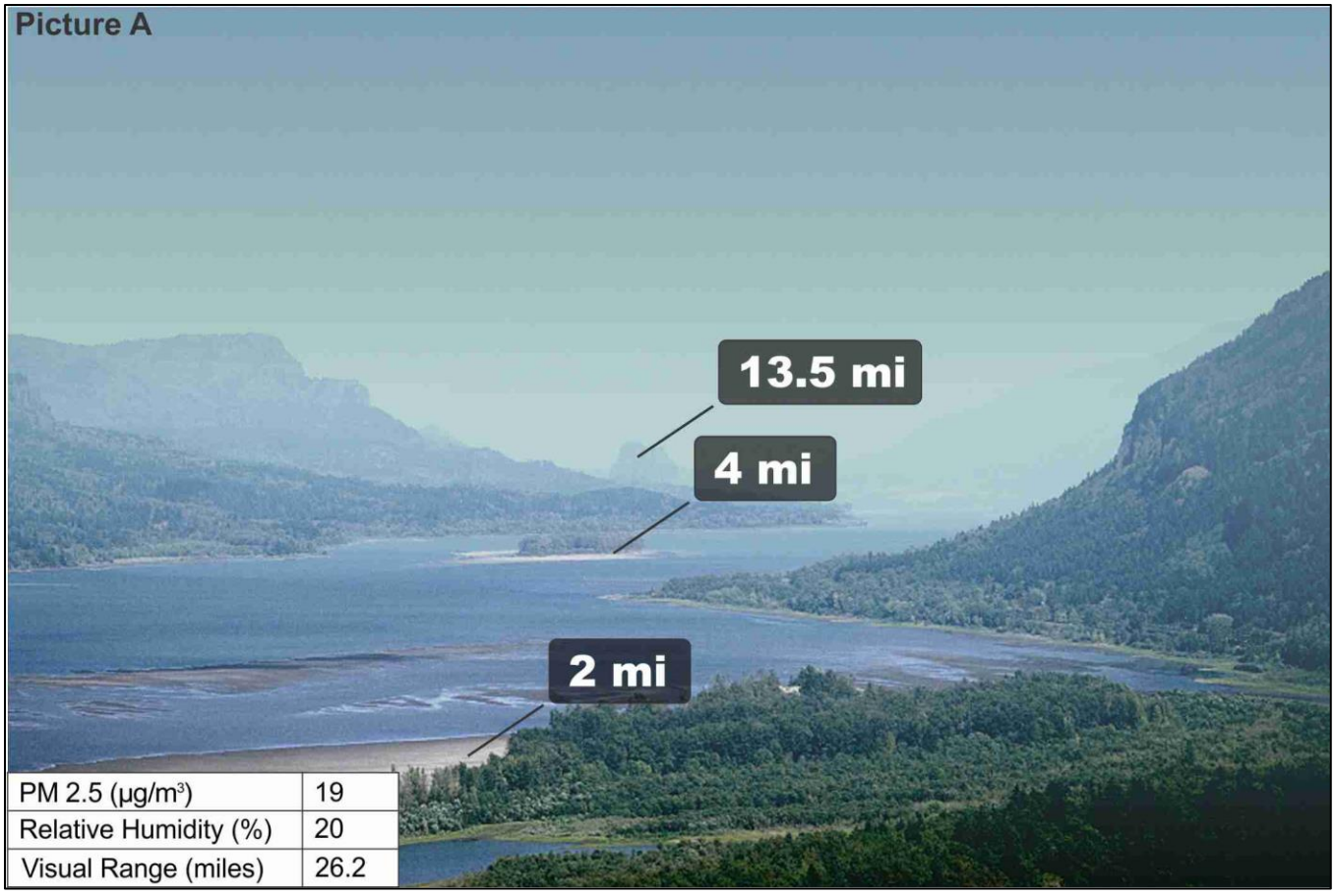
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	1.48	2.56	2.56	2.56
Ammonium nitrate	0.77	1.78	1.78	1.78
Organic carbon	2.32	12.56	101.75	224.75
LAC/Black carbon	0.47	0.82	6.63	14.63
Fine soil	0.66	1.28	1.28	1.28
Coarse mass	7.90	11.88	11.88	24.50

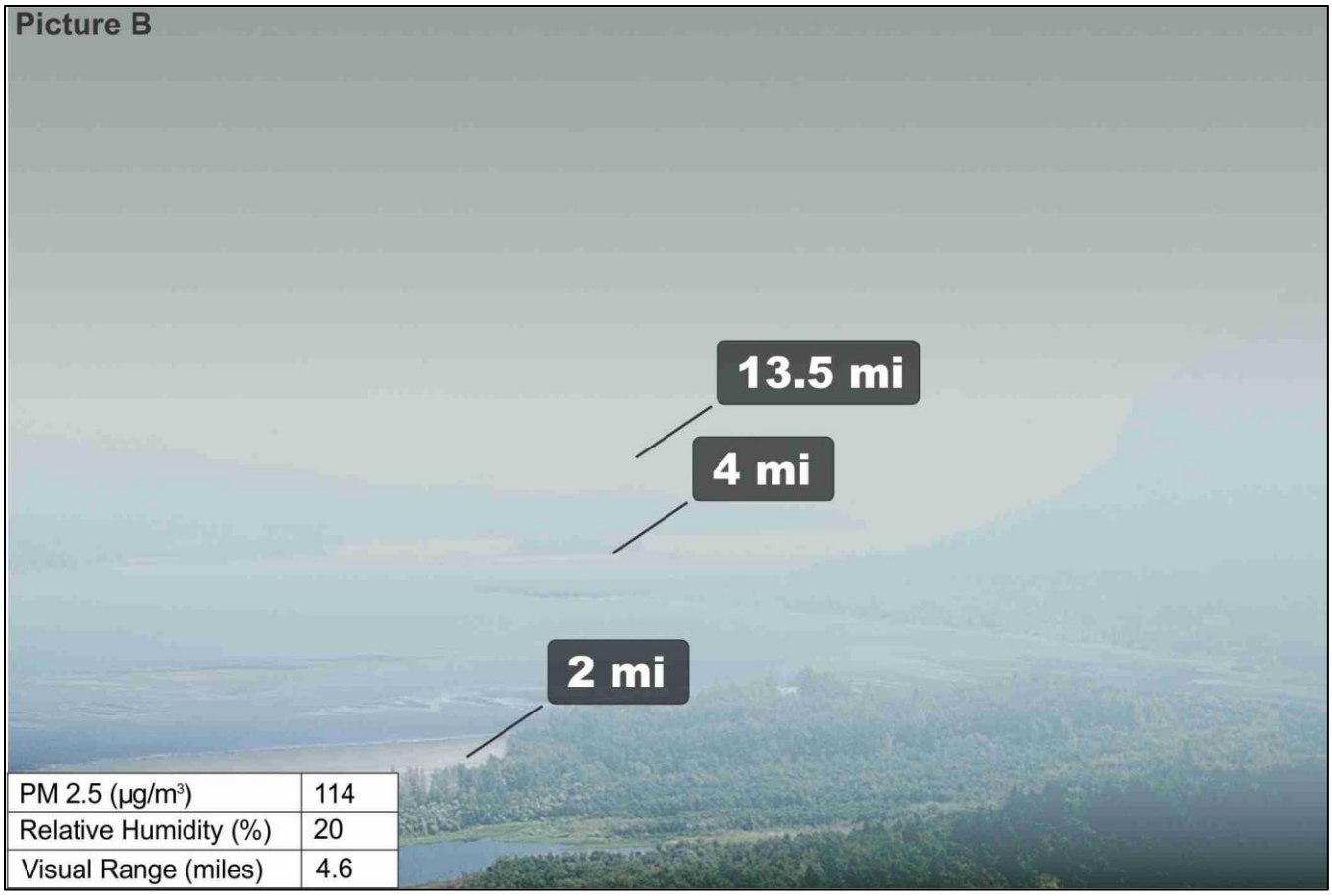
Table 15—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in the Columbia River Gorge, OR

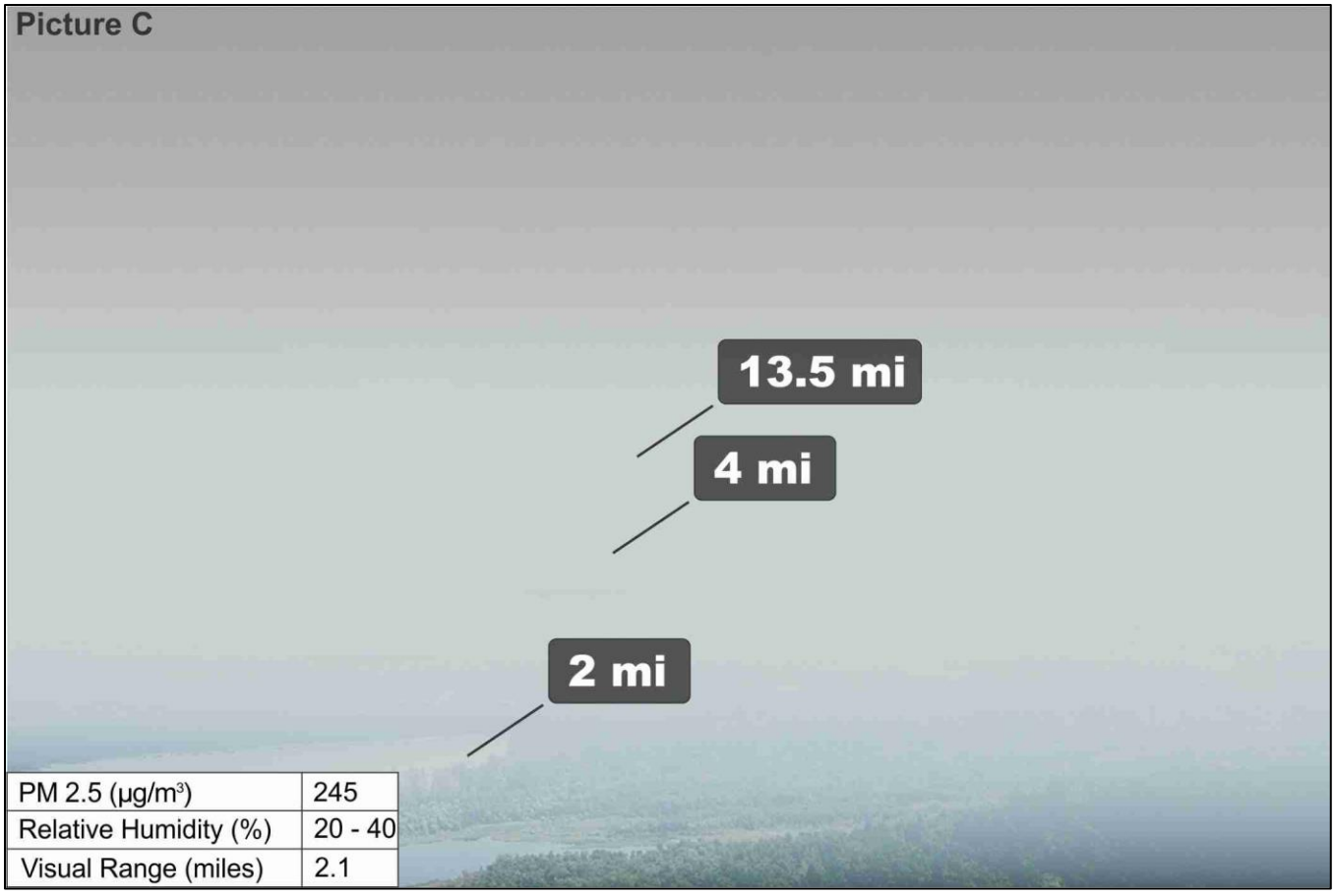
$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	40	66.5	107.0
19 (picture A)	40	25.4	40.8
	50	24.2	39.0
	60	22.9	36.9
	70	21.5	34.6
	80	19.9	32.0
114 (picture B)	40	4.4	7.2
	50	4.3	7.0
	60	4.2	6.8
	70	4.1	6.6
	80	4.0	6.4
245 (picture C)	40	2.1	3.3
	50-60	2.0	3.2
	70-80	1.9	3.1

COLUMBIA RIVER GORGE, OR






Picture B
13.5 mi
4 mi
2 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 20
Visual Range (miles) 4.6


Picture C
13.5 mi
4 mi
2 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 20 - 40
Visual Range (miles) 2.1

U.S. Forest Service, Region 6 – Snoqualmie Pass, WA

Particulate data from 353 days of sampling (December 1993 to May 1999) at Snoqualmie Pass were chosen to represent baseline and elevated regional air quality concentrations (table 16). The baseline image represents an area free of smoke-impaired visibility (<5 μg · m^{-3} fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 μg · m^{-3}) and RH are noted (table 17) and illustrated for the Snoqualmie Pass on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Seattle-Tacoma International Airport, WA (NOAA 2014).

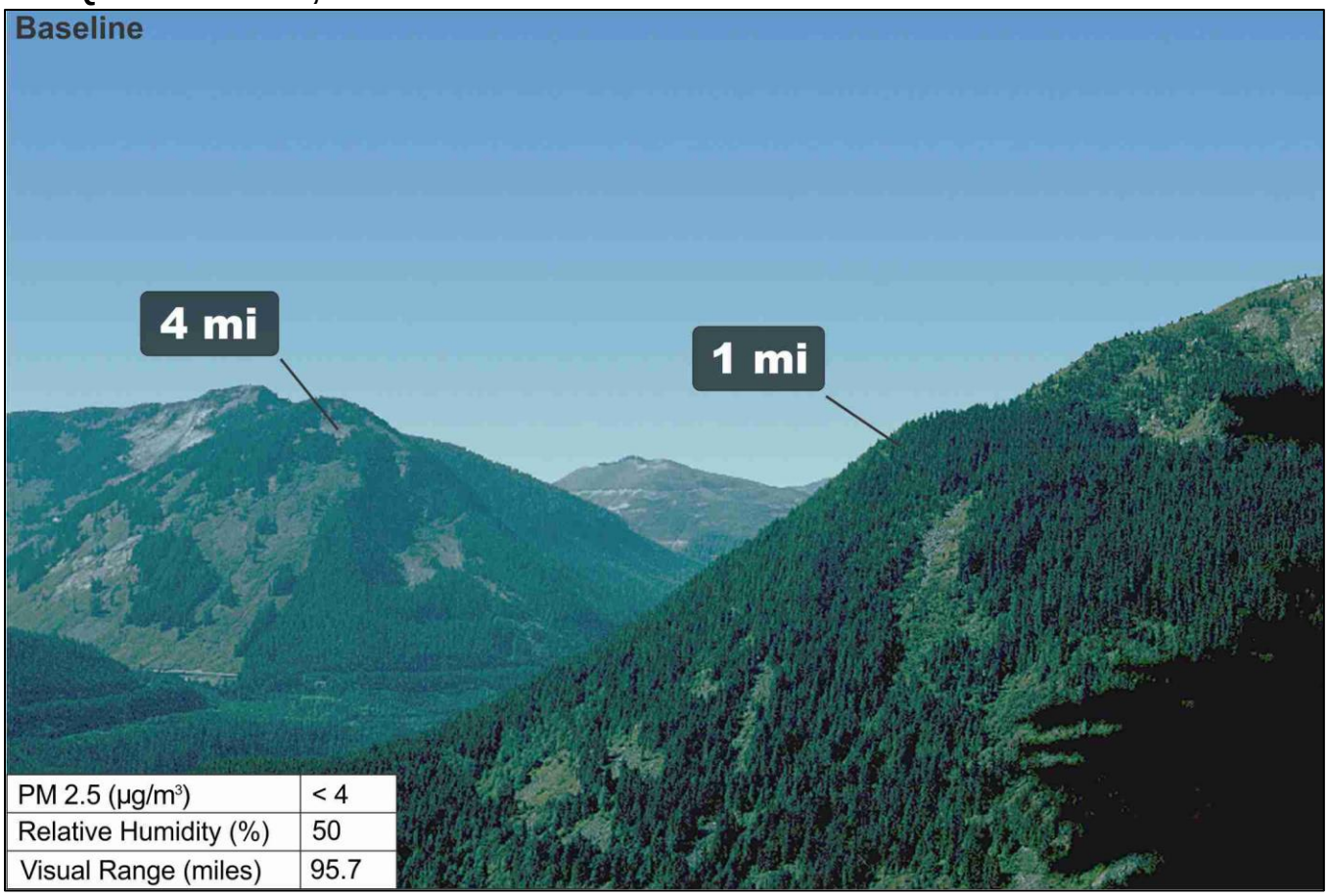
Table 16—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels at Snoqualmie Pass, WA

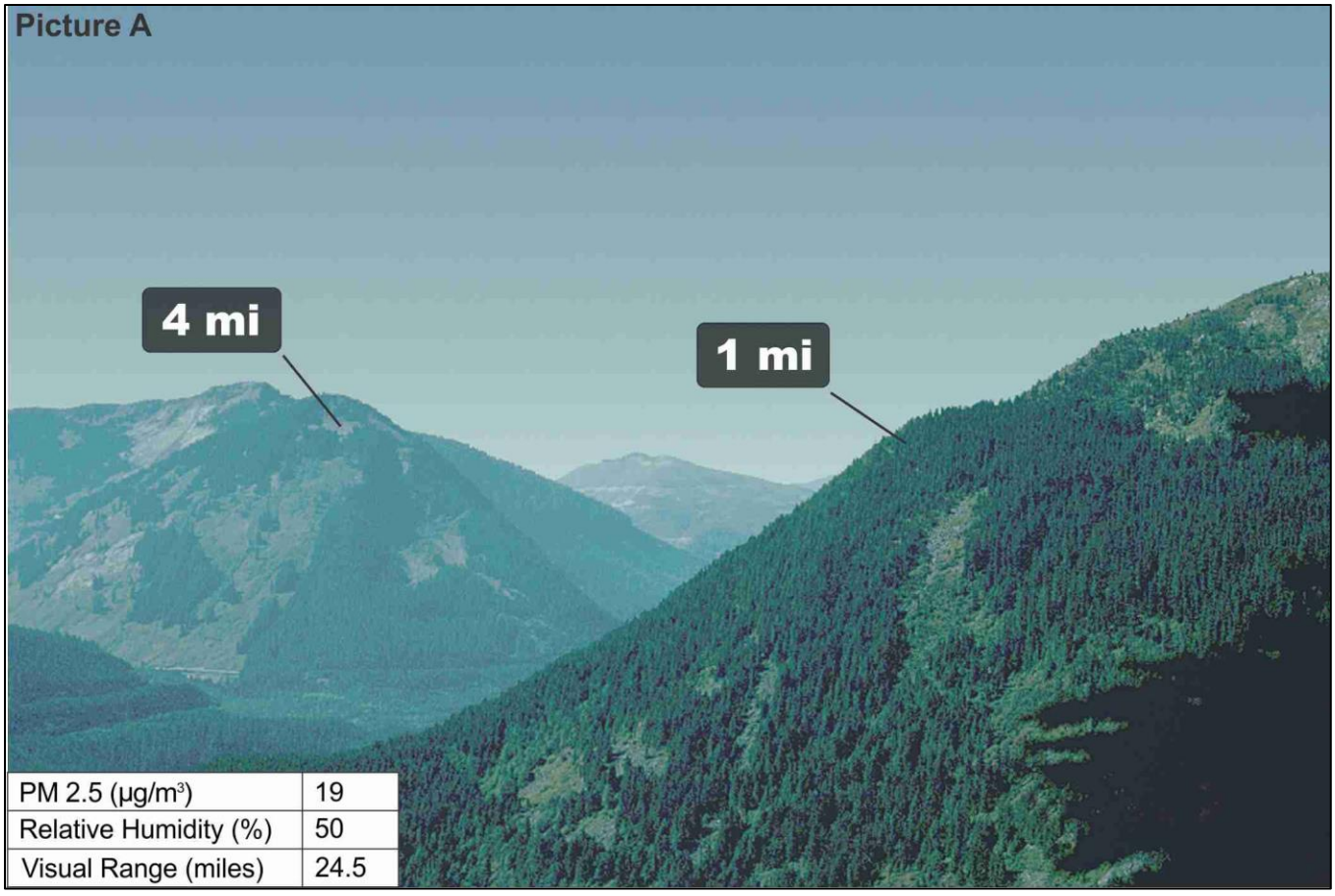
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- *μg · m*$^{-3}$ ----------			
Ammonium sulfate	0.98	1.84	1.84	1.84
Ammonium nitrate	0.35	0.59	0.59	0.59
Organic carbon	1.28	14.80	103.99	226.98
LAC/Black carbon	0.31	0.96	6.77	14.78
Fine soil	0.29	0.81	0.81	0.81
Coarse mass	2.94	3.82	11.40	24.50

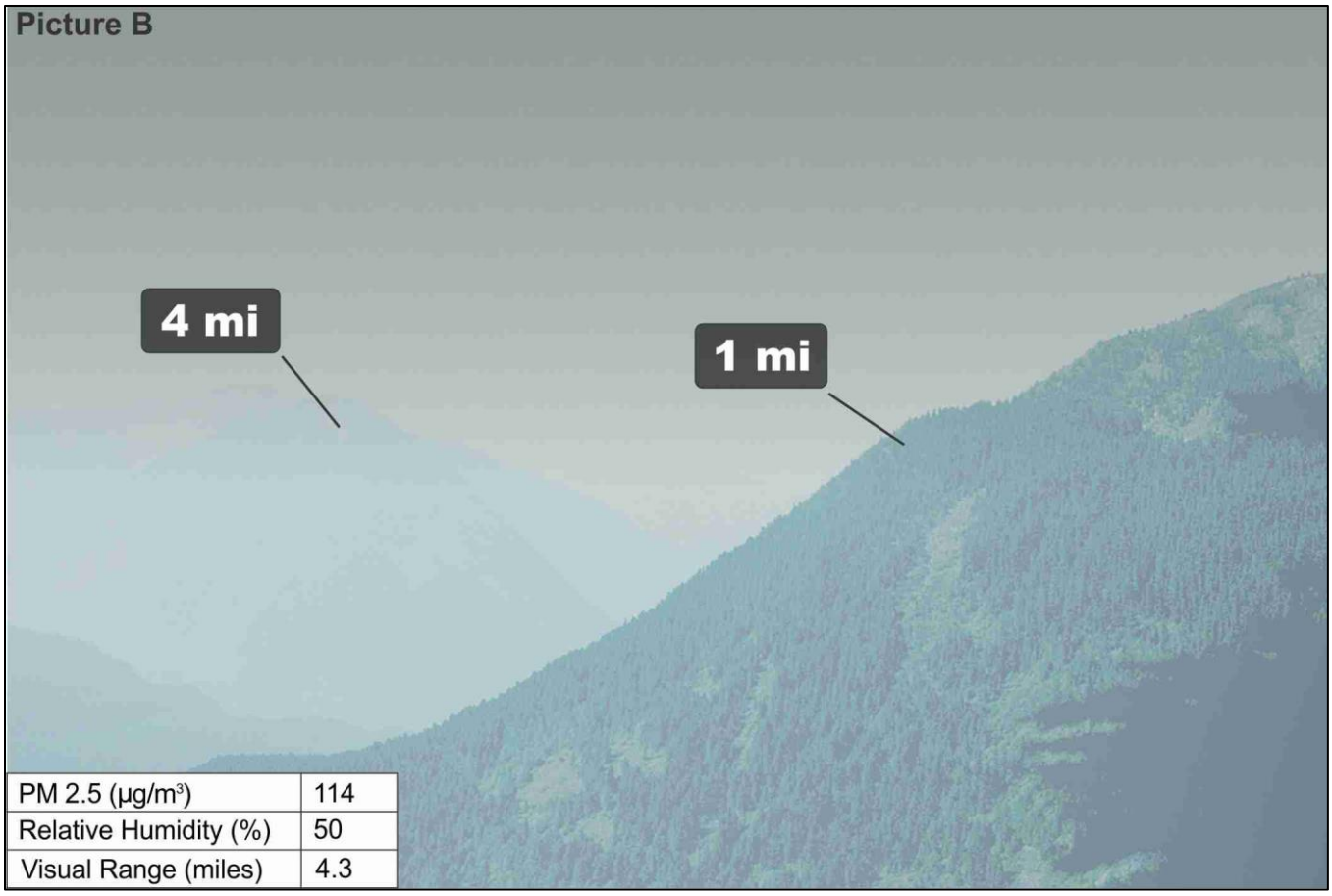
Table 17—Visual range as a function of $PM_{2.5}$ concentration and relative humidity at Snoqualmie Pass, WA

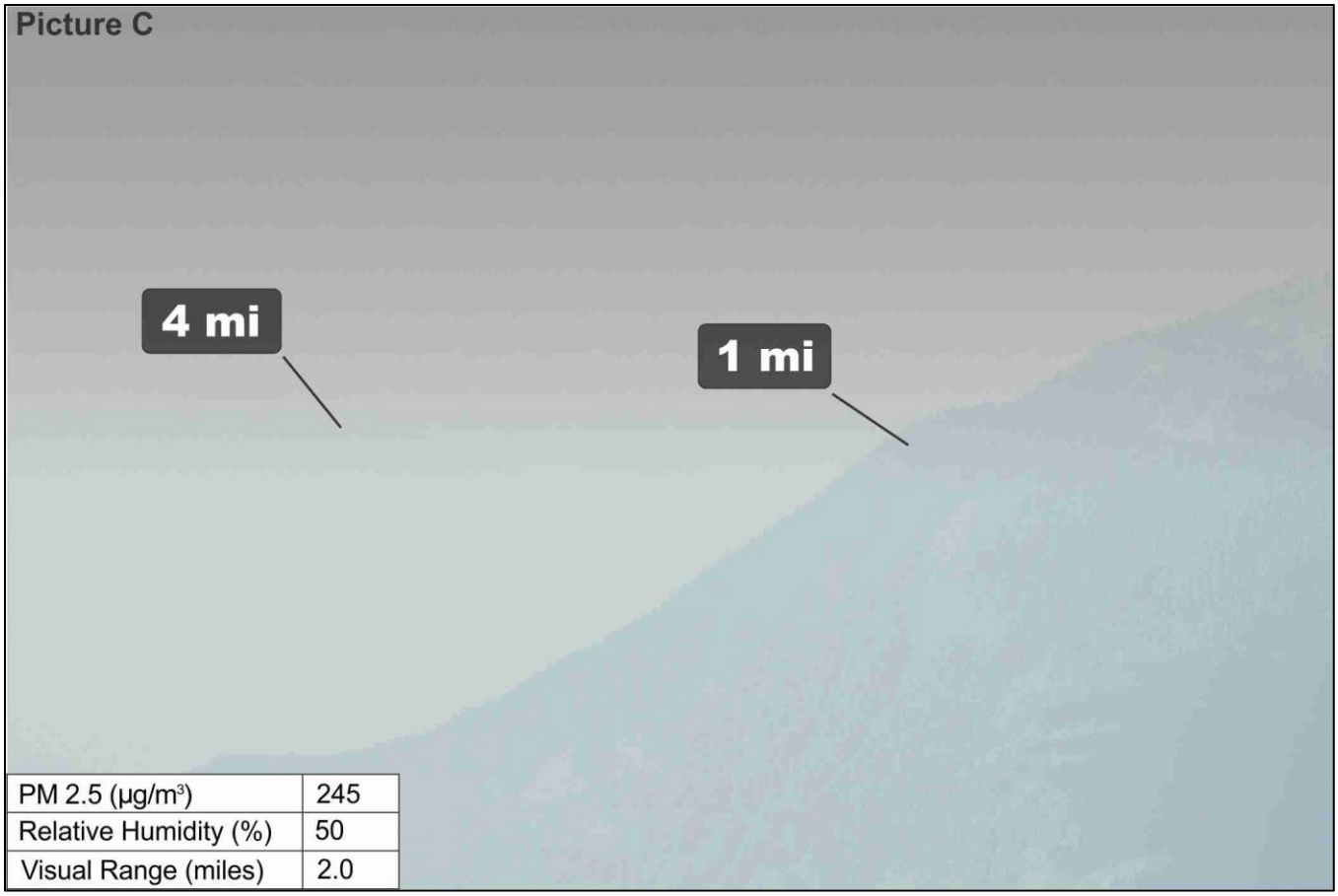
$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
μg · m^{-3}	*percent*	*miles*	*km*
<5 (baseline)	50	95.7	154.0
19 (picture A)	50	24.5	39.5
	60	23.6	38.0
	70	22.6	36.3
	80	21.4	34.4
	90	19.7	31.7
114 (picture B)	50	4.3	7.0
	60	4.2	6.8
	70	4.1	6.6
	80	4.0	6.5
	90	3.9	6.3
245 (picture C)	50	2.0	3.2
	60	2.0	3.2
	70-90	1.9	3.1

SNOQUALMIE PASS, WA






Picture B
4 mi
1 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 50
Visual Range (miles) 4.3


Picture C
4 mi
1 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 50
Visual Range (miles) 2.0

U.S. Forest Service, Region 8 – Great Smoky Mountains National Park, TN

Particulate data from 935 days (March 1988 to May 1999) at Great Smoky Mountains National Park were chosen to represent baseline and elevated regional air quality concentrations (table 18). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 19) and illustrated for Great Smoky Mountains Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Great Smoky Mountains National Park (EPA 2014).

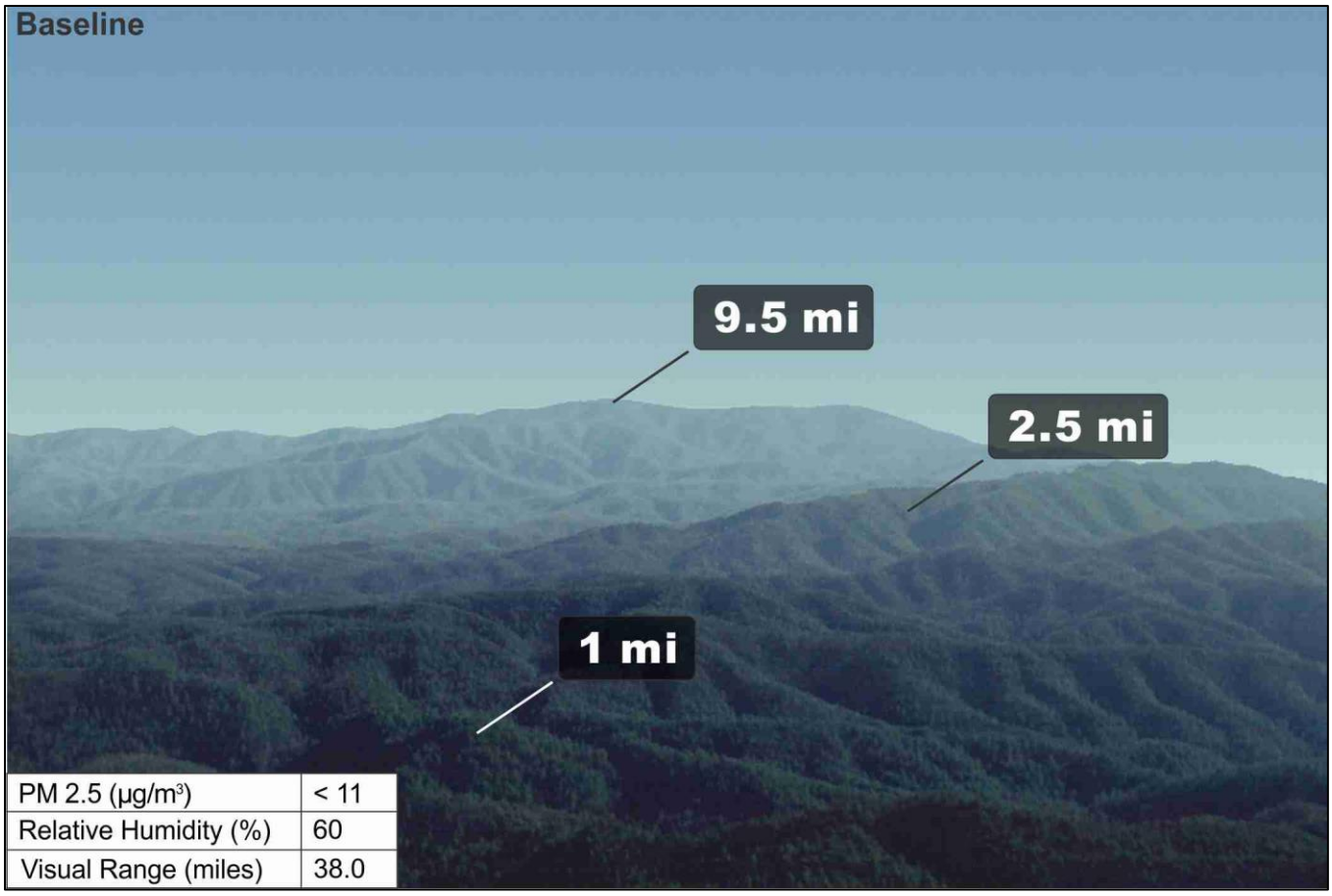
Table 18—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Great Smoky Mountains National Park, TN

Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	6.42	13.97	13.97	13.97
Ammonium nitrate	0.43	0.31	0.31	0.31
Organic carbon	2.78	3.46	92.66	215.65
LAC/Black carbon	0.47	0.23	6.03	14.04
Fine soil	0.55	1.03	1.03	1.03
Coarse mass	5.74	7.23	11.40	24.50

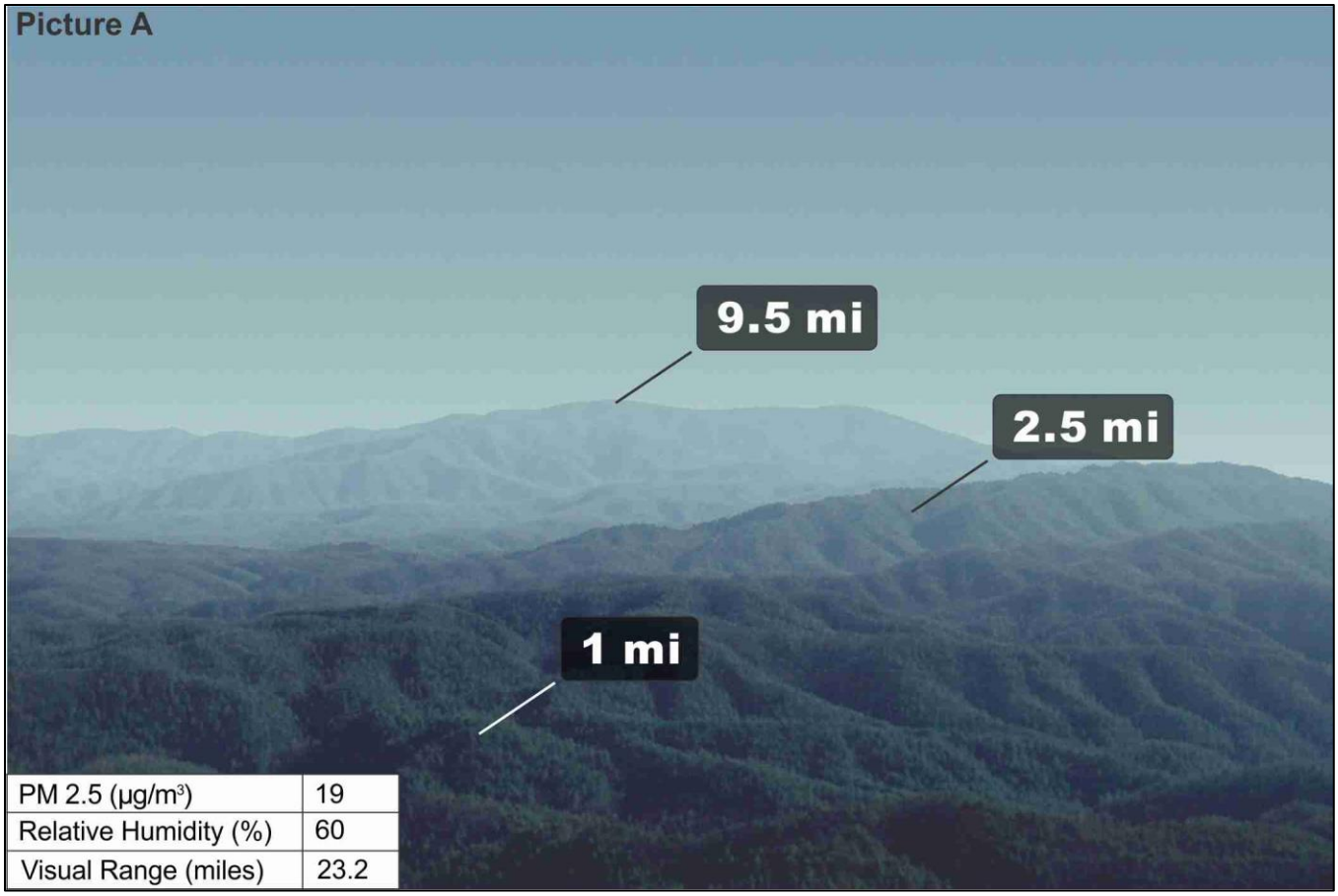
Table 19—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Great Smoky Mountains National Park, TN

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	60	38.0	61.2
19 (picture A)	60	23.2	37.4
	70	19.6	31.5
	80	16.2	26.0
114 (picture B)	60	4.2	6.8
	70	4.0	6.5
	80	3.8	6.1
245 (picture C)	60	2.0	3.2
	70	1.9	3.1
	80	1.8	2.9

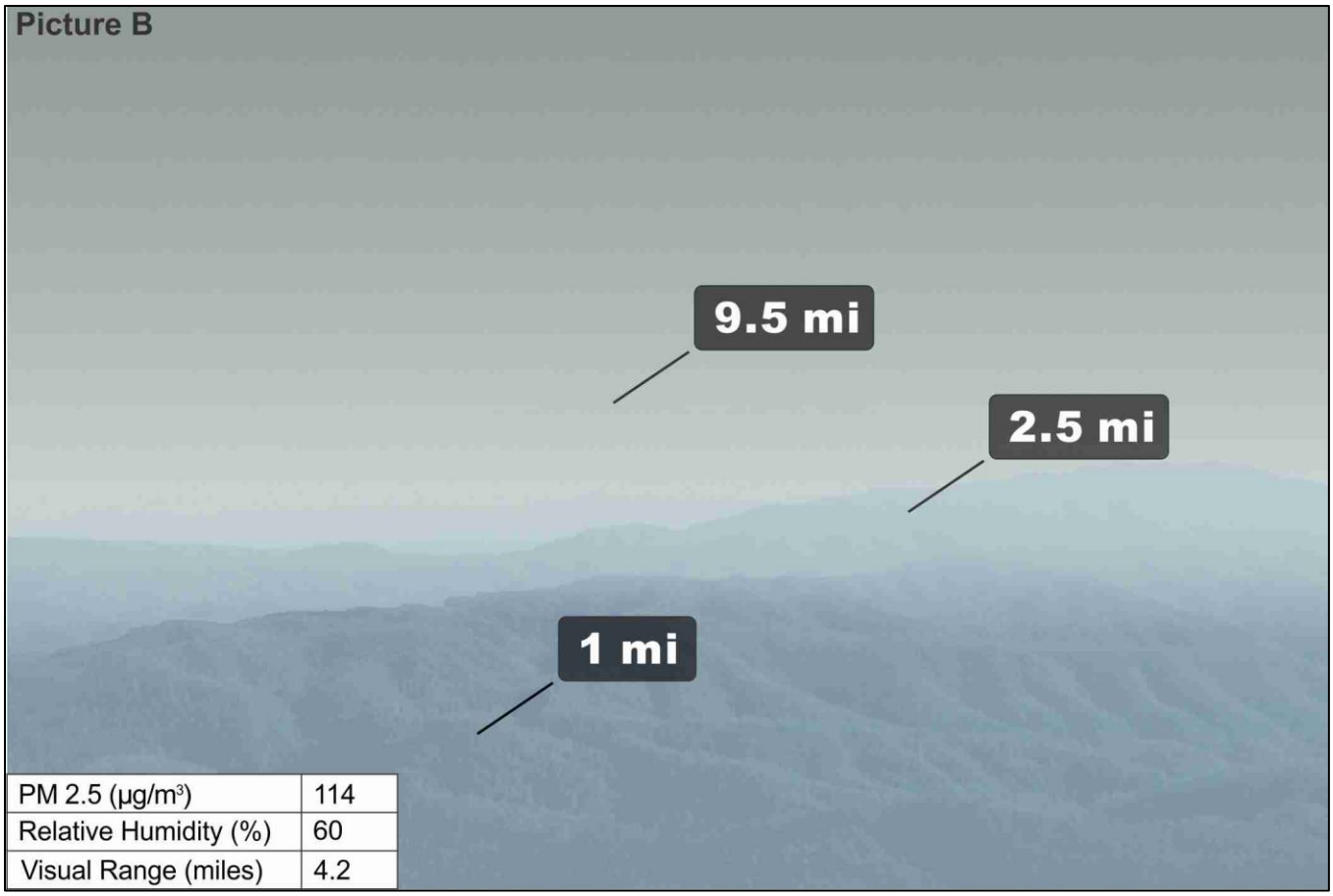
GREAT SMOKY MOUNTAINS NATIONAL PARK, TN



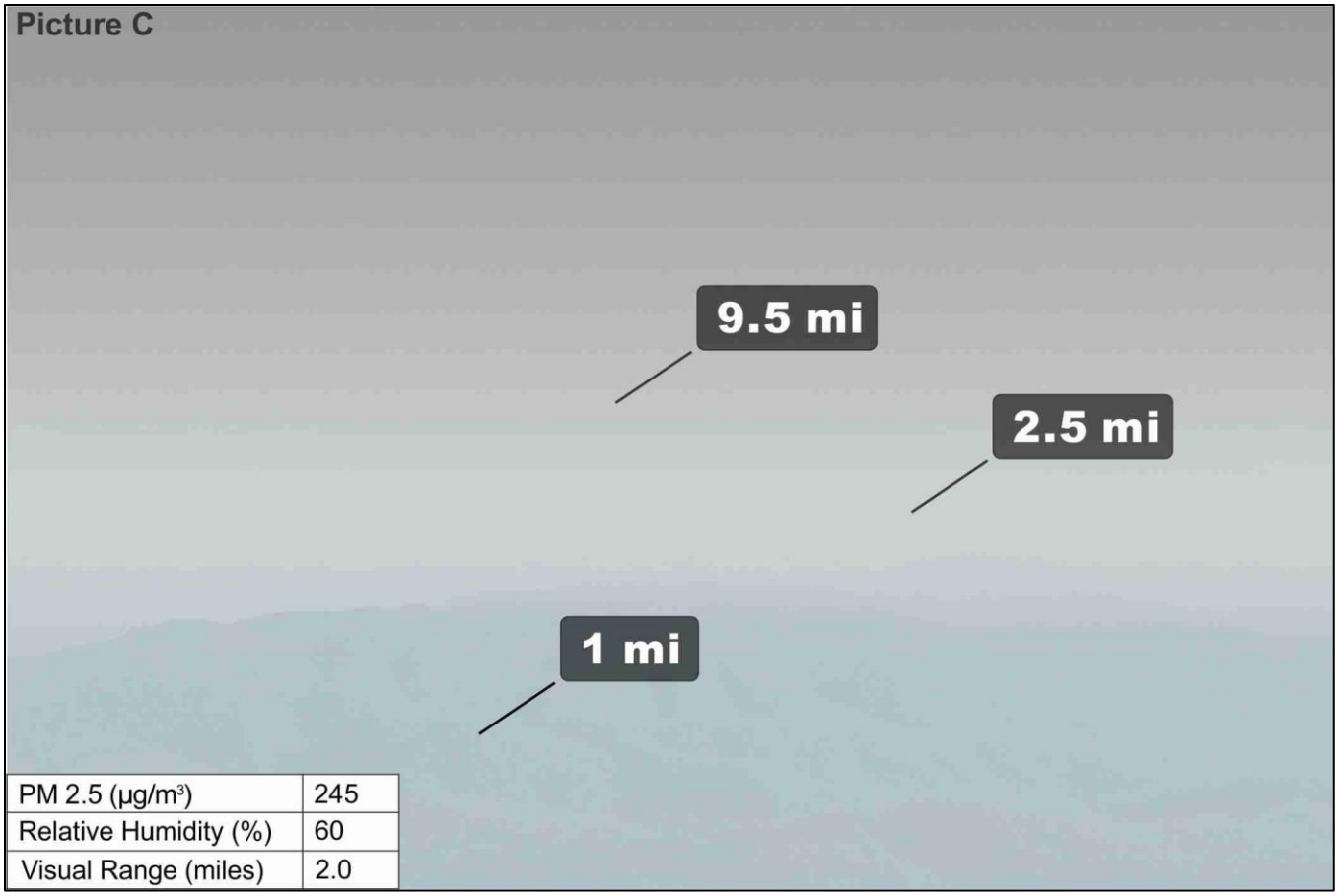
PM 2.5 (μg/m³)	< 11
Relative Humidity (%)	60
Visual Range (miles)	38.0



PM 2.5 (μg/m³)	19
Relative Humidity (%)	60
Visual Range (miles)	23.2



PM 2.5 (µg/m³)	114
Relative Humidity (%)	60
Visual Range (miles)	4.2



PM 2.5 (µg/m³)	245
Relative Humidity (%)	60
Visual Range (miles)	2.0

U.S. Forest Service, Region 8 – Mammoth Cave National Park, KY

Particulate data from 1,067 days of sampling (October 1991 to August 2003) at Mammoth Cave National Park were chosen to represent baseline and elevated regional air quality concentrations (table 20). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 21) and illustrated for Mammoth Cave National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Mammoth Cave National Park (EPA 2014).

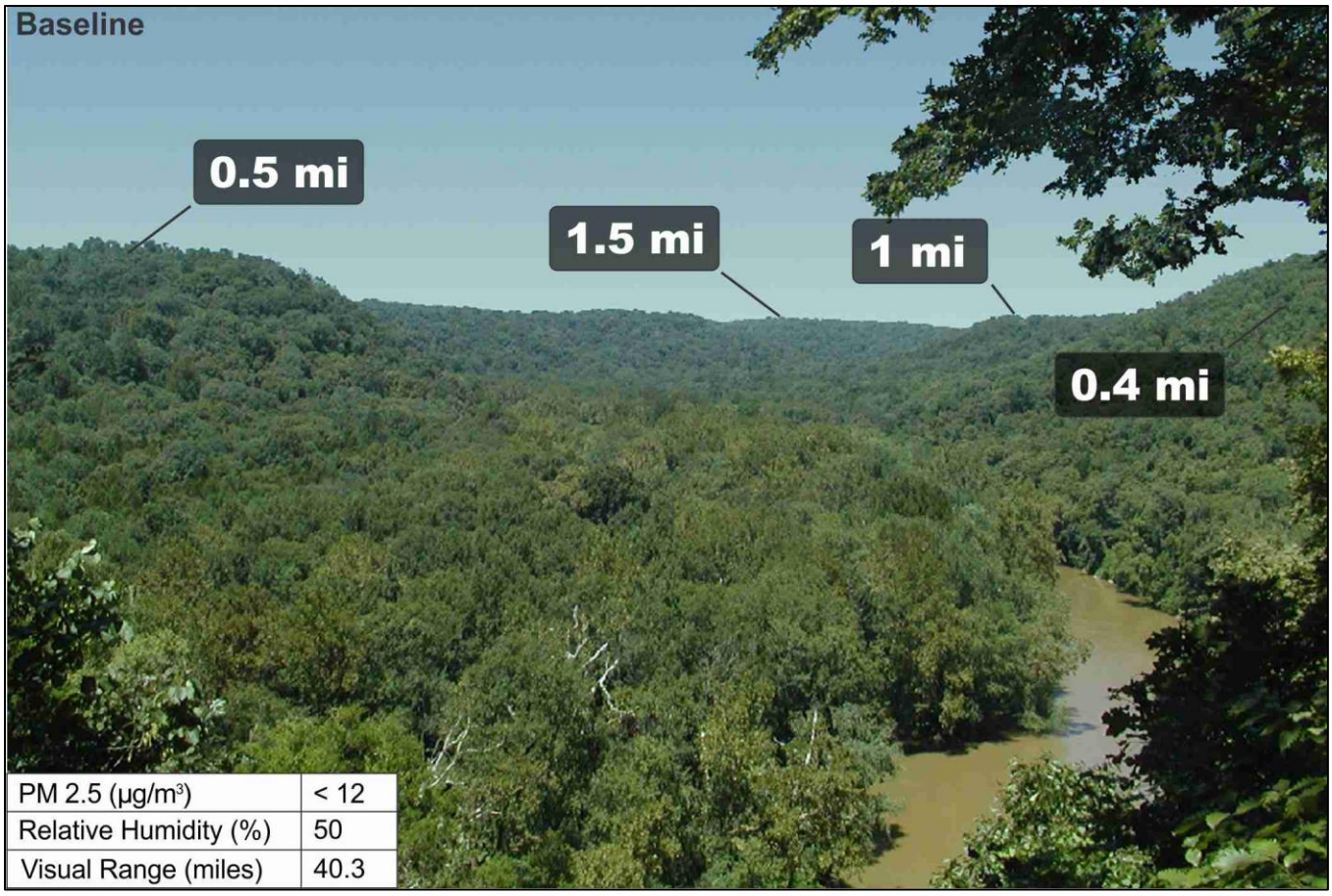
Table 20—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Mammoth Cave National Park, KY

Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	6.94	13.99	13.99	13.99
Ammonium nitrate	0.90	0.65	0.65	0.65
Organic carbon	2.82	3.03	92.22	215.22
LAC/Black carbon	0.48	0.20	6.01	14.01
Fine soil	0.58	1.13	1.13	1.13
Coarse mass	4.43	6.26	11.40	24.50

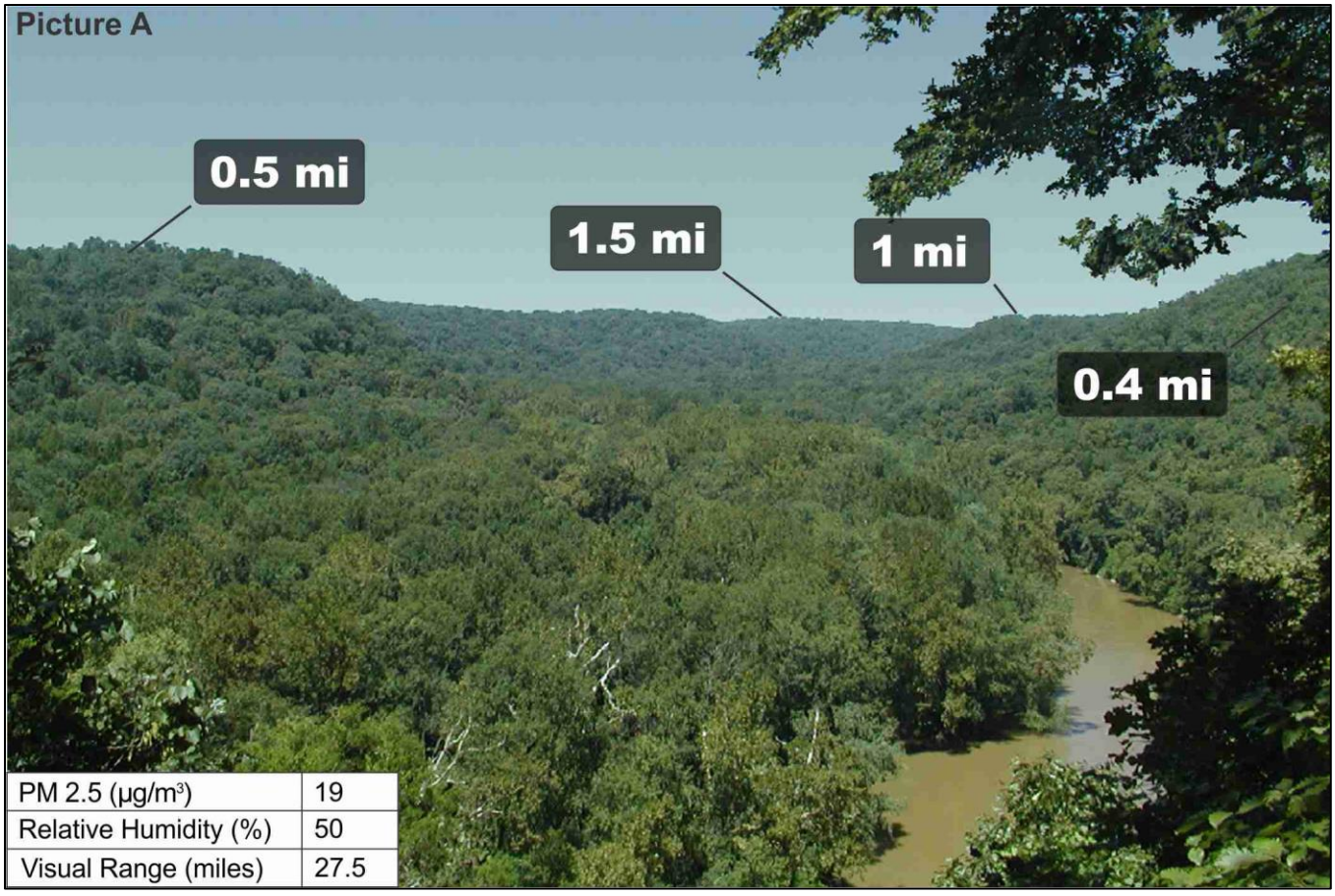
Table 21—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Mammoth Cave National Park, KY

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	50	40.3	64.8
19 (picture A)	50	27.5	44.2
	60	23.4	37.7
	70	19.6	31.6
	80	16.2	26.0
114 (picture B)	50	4.4	7.1
	60	4.2	6.8
	70	4.0	6.5
	80	3.8	6.1
245 (picture C)	50	2.0	3.3
	60	2.0	3.2
	70	1.9	3.1
	80	1.8	2.9

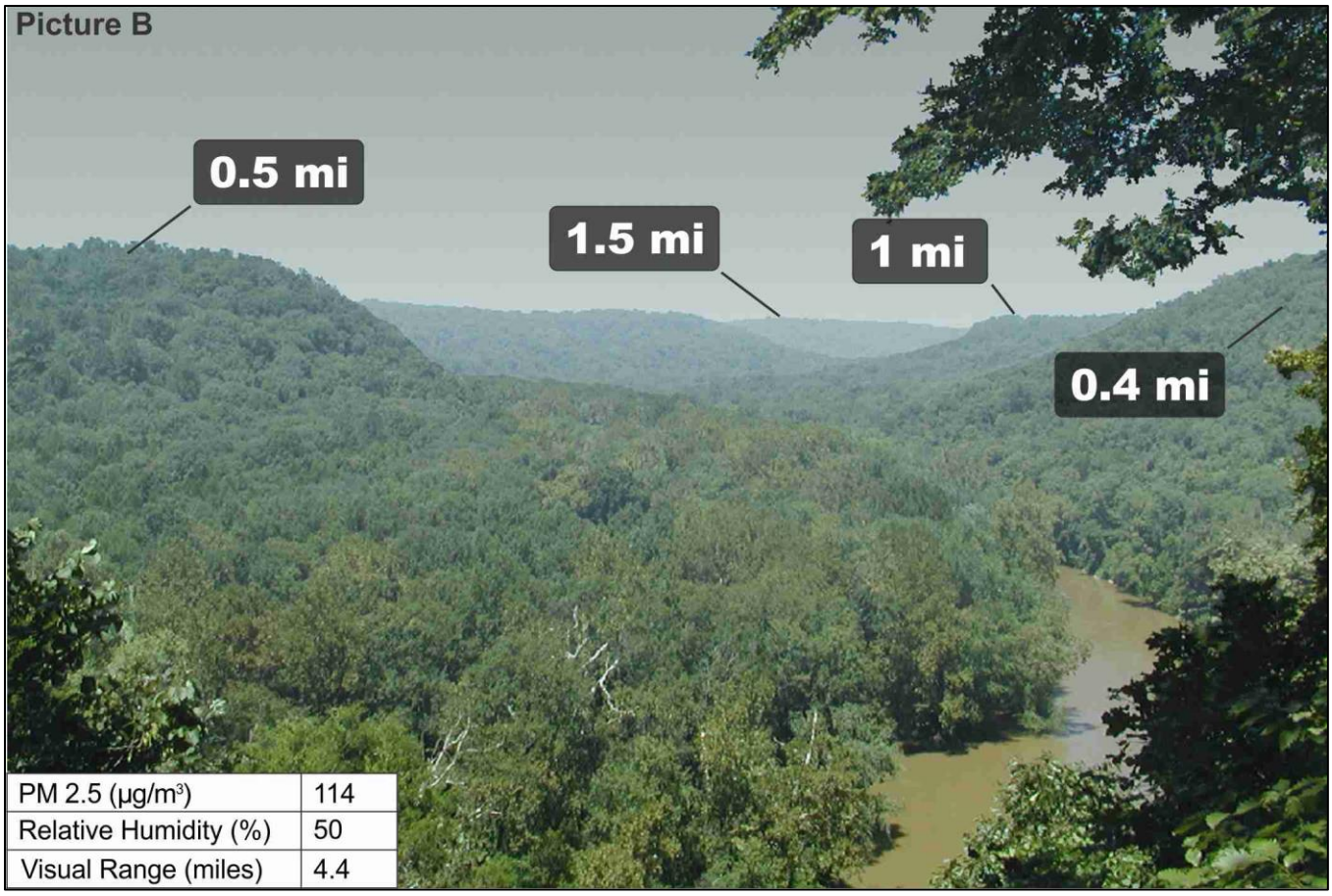
MAMMOTH CAVE NATIONAL PARK, KY



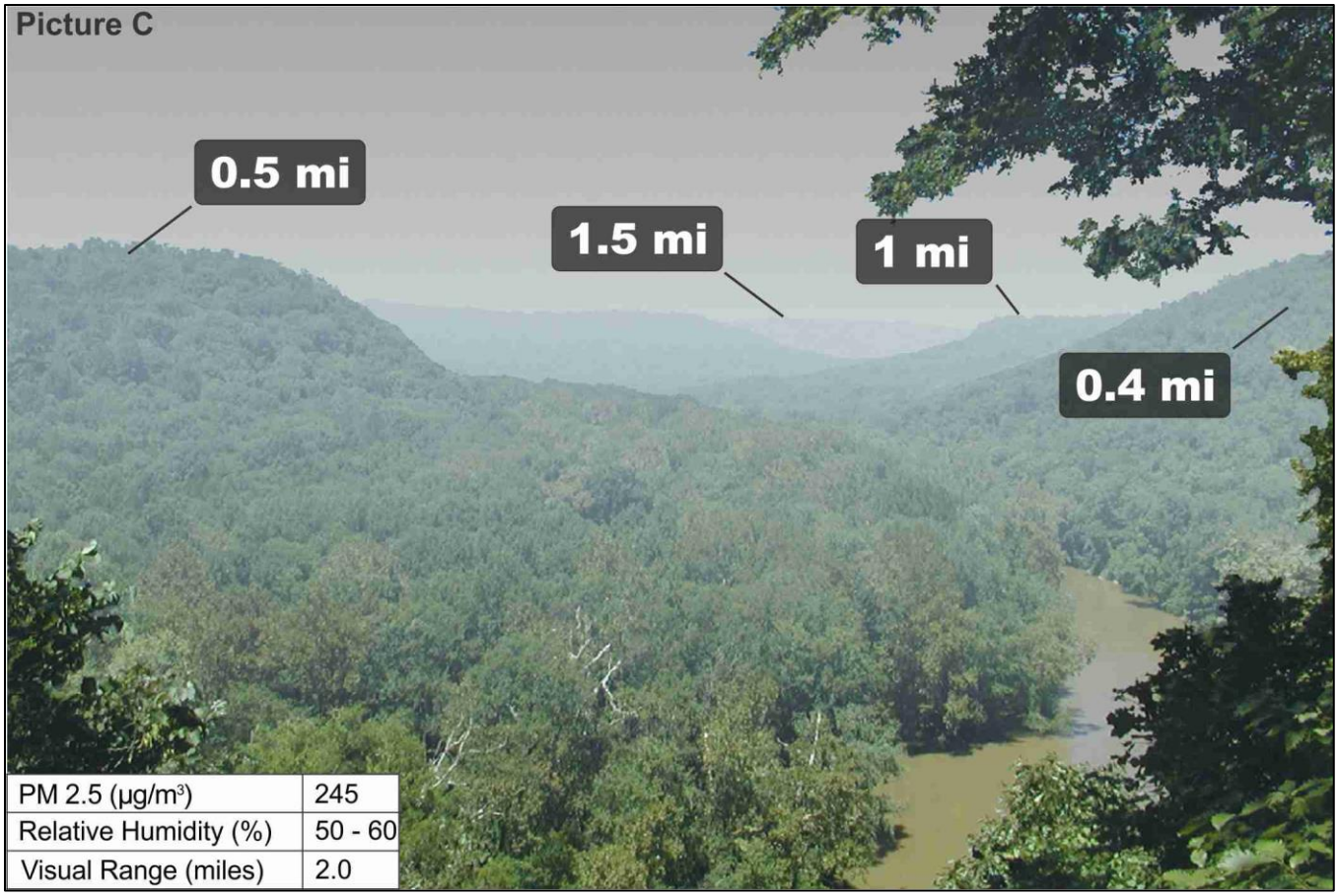
PM 2.5 (µg/m³)	< 12
Relative Humidity (%)	50
Visual Range (miles)	40.3



PM 2.5 (µg/m³)	19
Relative Humidity (%)	50
Visual Range (miles)	27.5



PM 2.5 (µg/m³)	114
Relative Humidity (%)	50
Visual Range (miles)	4.4



PM 2.5 (µg/m³)	245
Relative Humidity (%)	50 - 60
Visual Range (miles)	2.0

U.S. Forest Service, Region 8 – Big Bend National Park, TX

Particulate data from 973 days of sampling (March 1988 to May 1999) at Big Bend National Park were chosen to represent baseline and elevated regional air quality concentrations (table 22). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 23) and illustrated for Big Bend National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Big Bend National Park (EPA 2014).

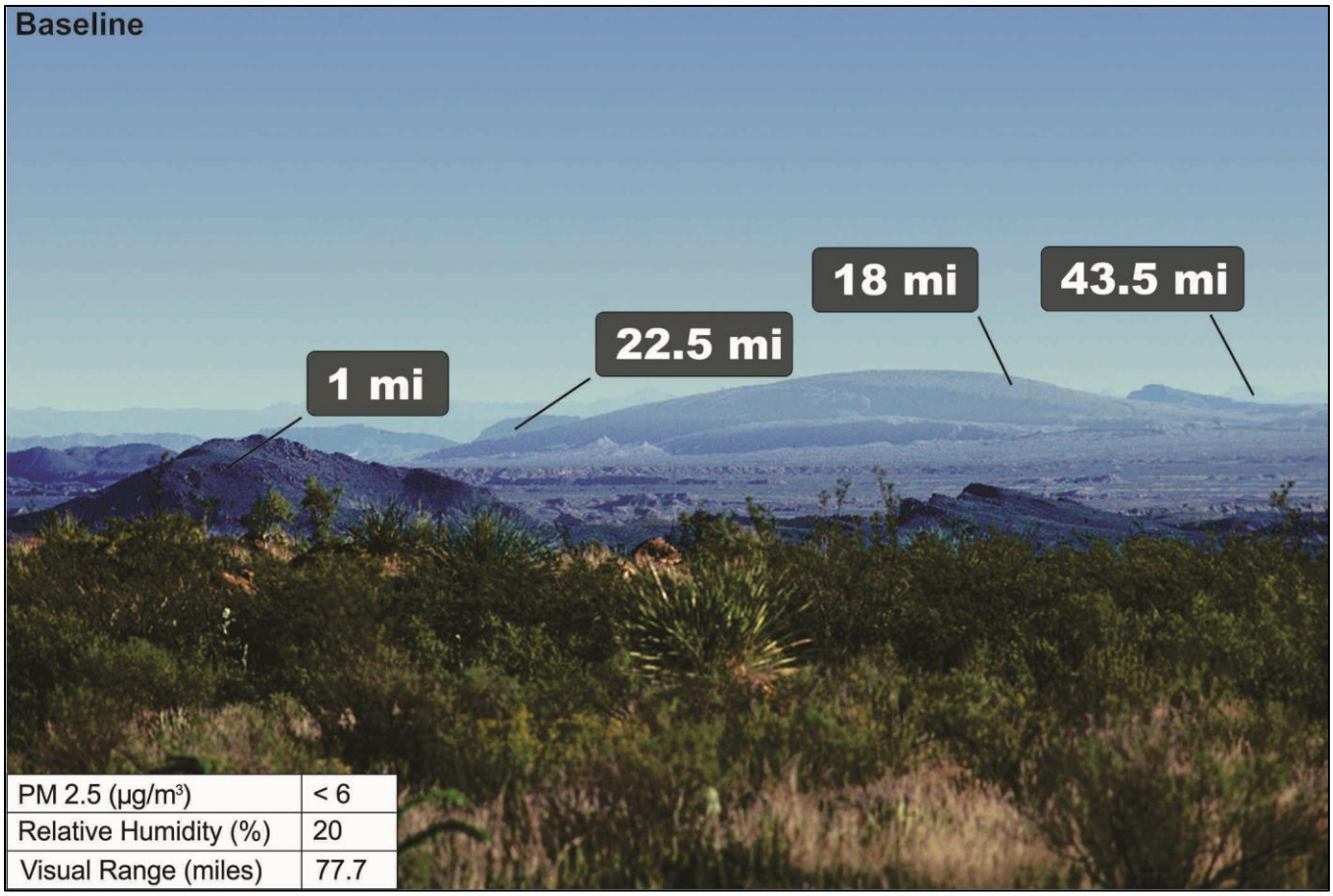
Table 22—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Big Bend National Park, TX

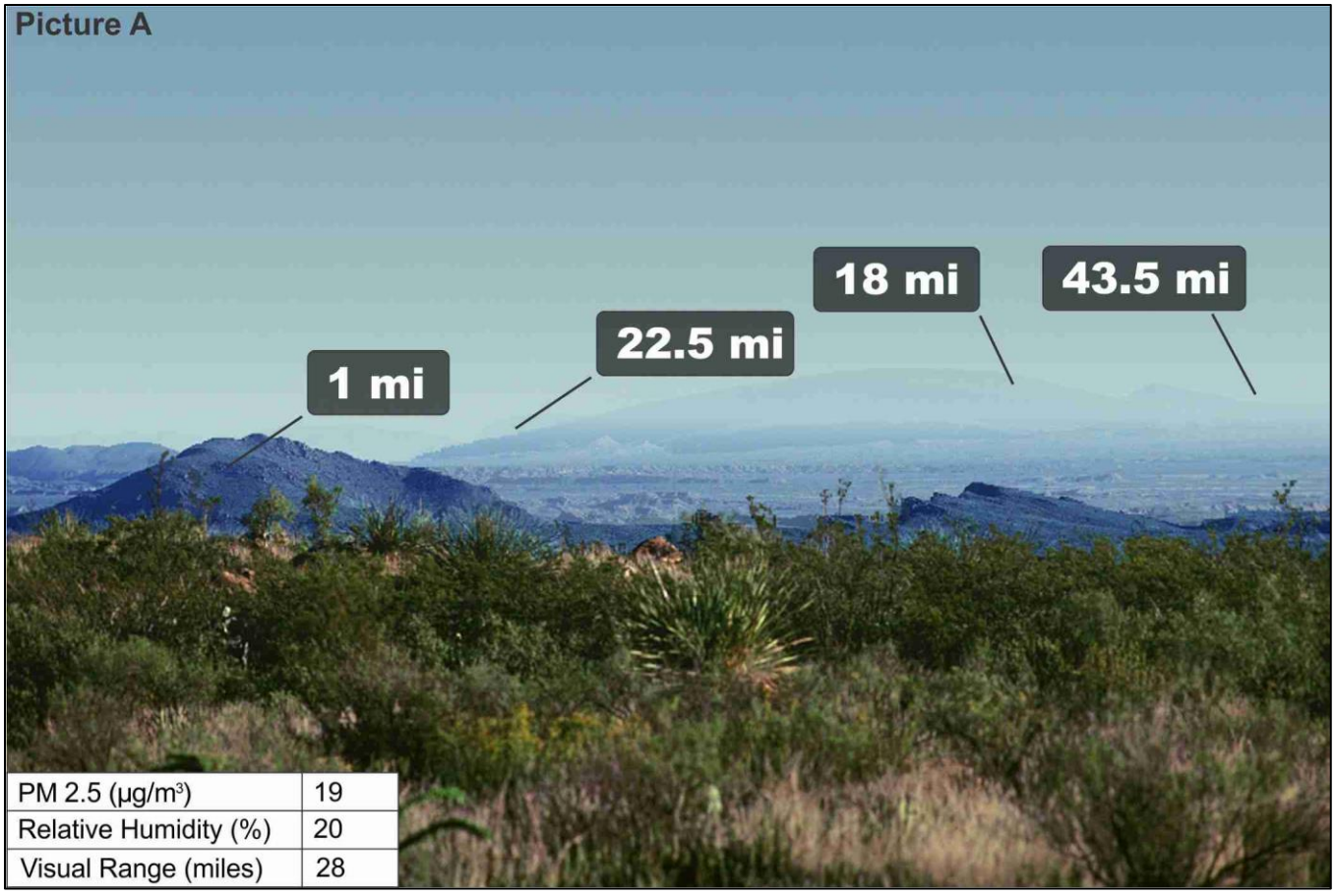
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	2.47	4.31	4.31	4.31
Ammonium nitrate	0.24	0.42	0.42	0.42
Organic carbon	1.3	10.89	100.08	223.07
LAC/Black carbon	0.21	0.71	6.52	14.53
Fine soil	1.2	2.67	2.67	2.67
Coarse mass	7.69	11.82	11.82	24.50

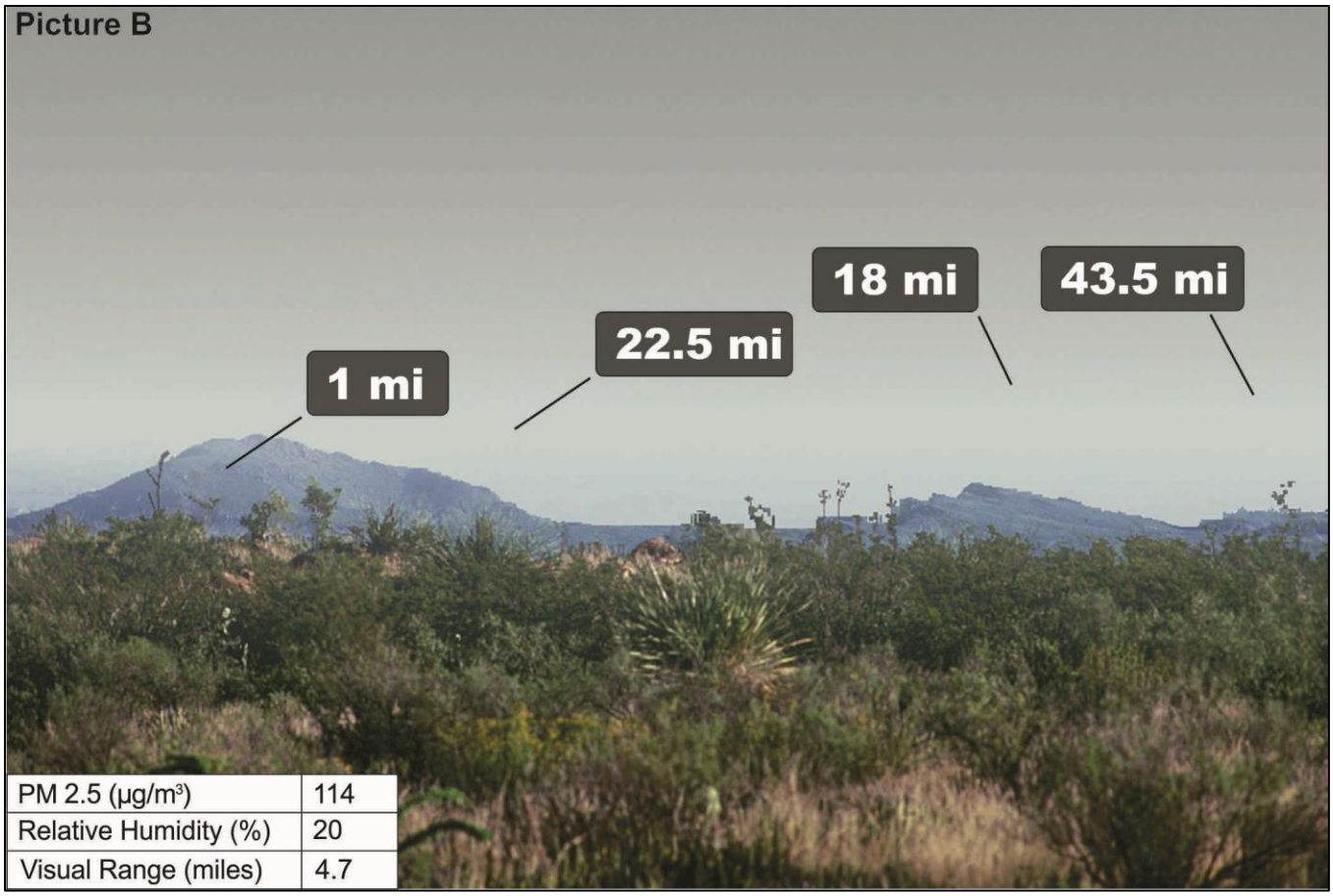
Table 23—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Big Bend National Park, TX

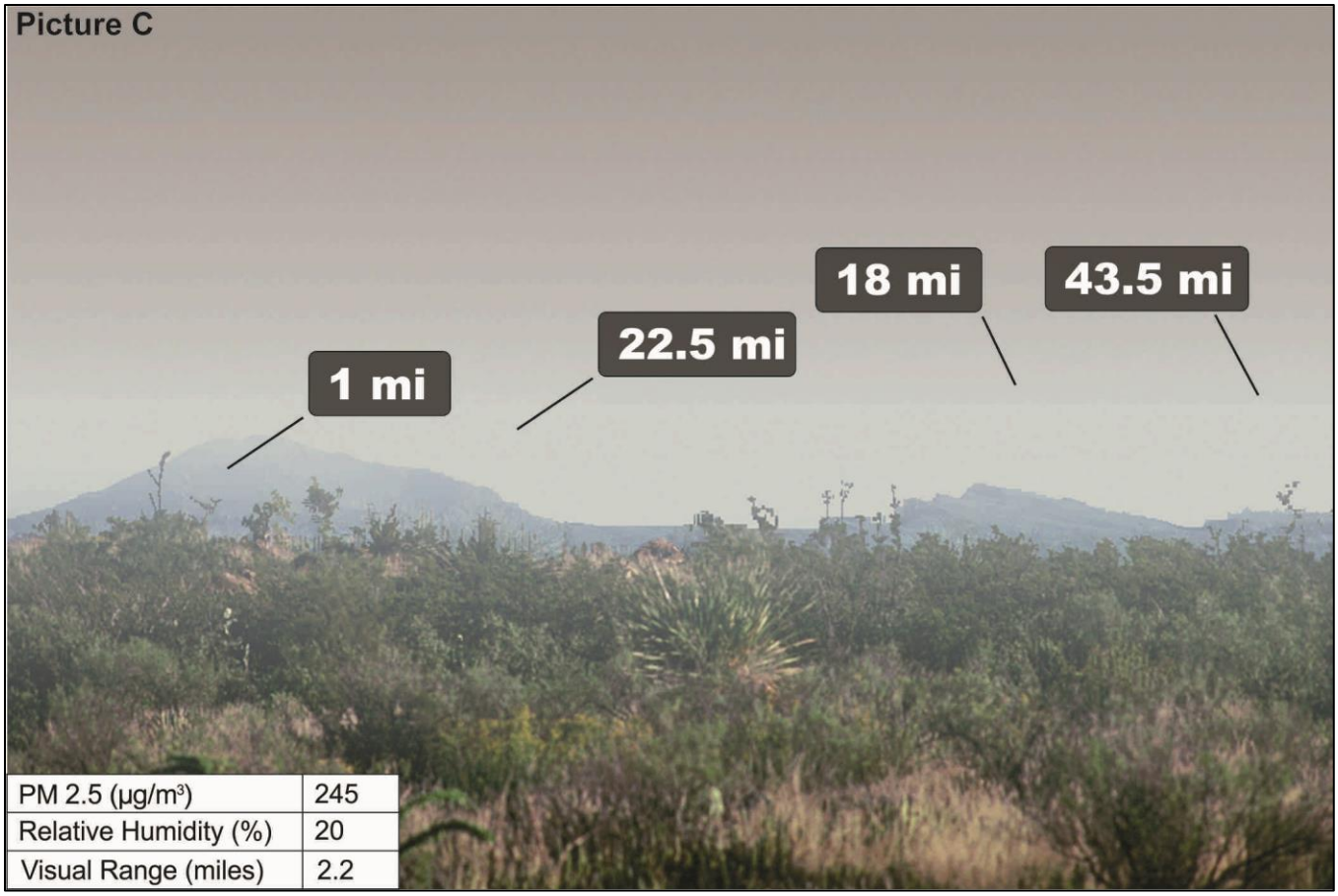
$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	20	77.7	125.0
19 (picture A)	20	28.0	45.1
	30	27.7	44.5
	40	27.0	43.5
	50	25.7	41.3
	60	24.2	38.9
	70	22.5	36.2
114 (picture B)	20	4.7	7.5
	30	4.6	7.4
	40	4.5	7.2
	50	4.4	7.1
	60	4.3	6.9
	70	4.2	6.7
245 (picture C)	20	2.2	3.5
	30-40	2.1	3.4
	50-60	2.0	3.2
	70	1.9	3.1

BIG BEND NATIONAL PARK, TX






Picture B
1 mi
22.5 mi
18 mi
43.5 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 20
Visual Range (miles) 4.7


Picture C
1 mi
22.5 mi
18 mi
43.5 mi
PM 2.5 (µg/m³) 245
Relative Humidity (%) 20
Visual Range (miles) 2.2

U.S. Forest Service, Region 9 – Acadia National Park, ME

Particulate data from 986 days of sampling (March 1988 to May 1999) at Acadia National Park were chosen to represent baseline and elevated regional air quality concentrations (table 24). The baseline image represents an area free of smoke-impaired visibility (<5 $\mu g \cdot m^{-3}$ fine and coarse particulates). Visual range at different levels of $PM_{2.5}$ concentration (19, 114, and 245 $\mu g \cdot m^{-3}$) and RH are noted (table 25) and illustrated for Acadia National Park on the following pages. Data used for estimating the effect of RH on visual range during the May-September fire season are from Acadia National Park (EPA 2014).

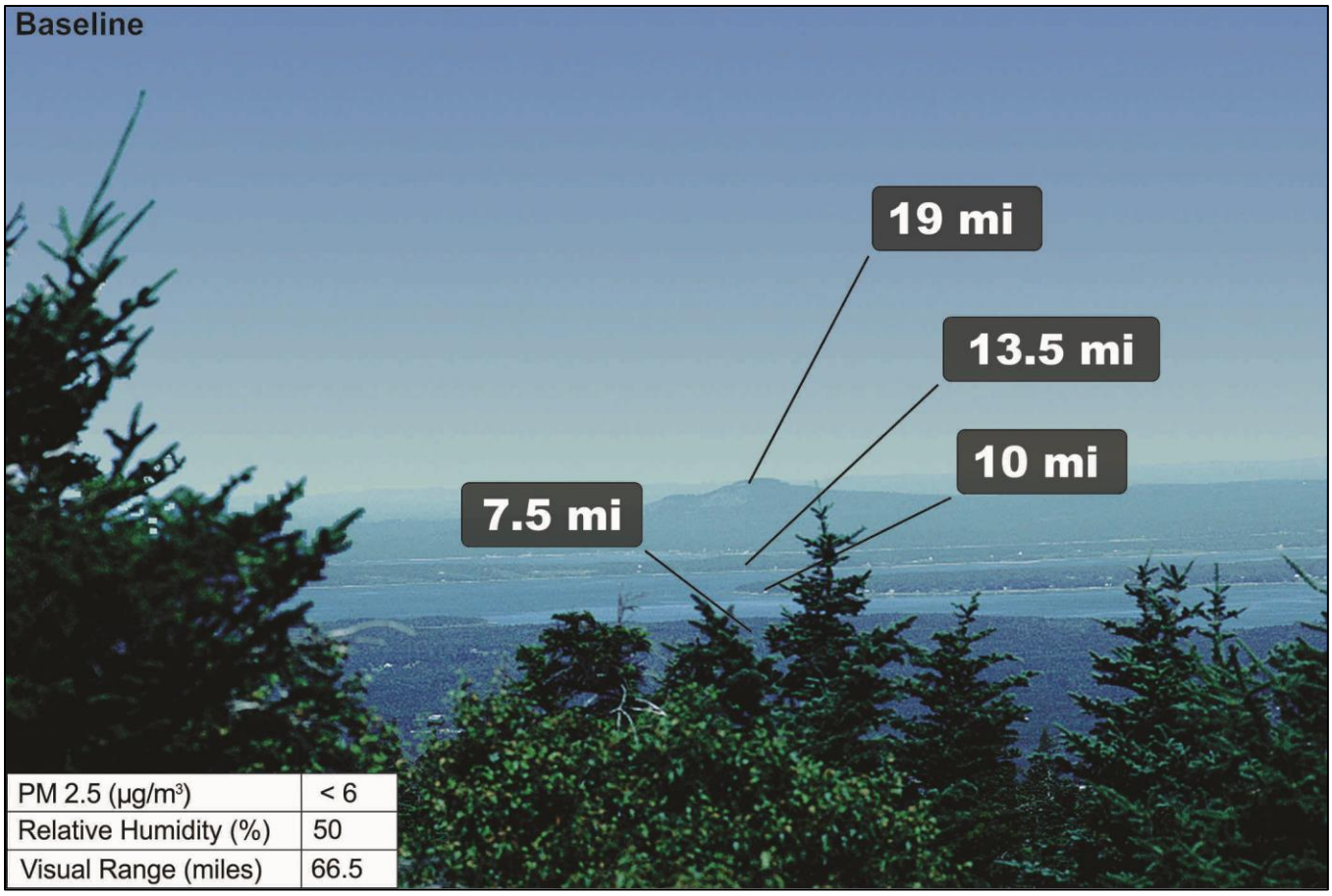
Table 24—Constituents of particulate matter ($PM_{2.5}$ and PM_{10}) at baseline and elevated levels in Acadia National Park, ME

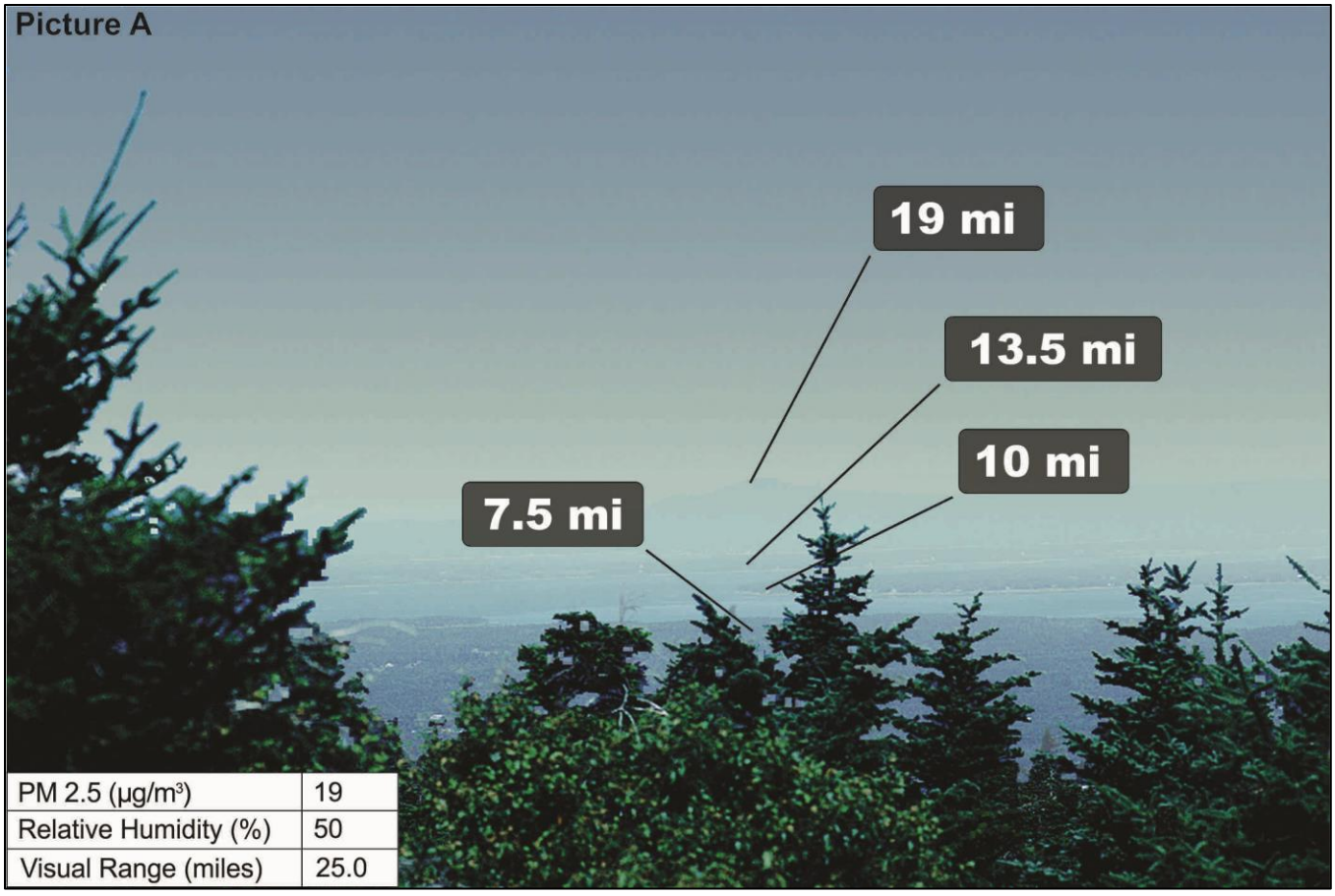
Particulate Matter	Particulate Matter Concentration			
Constituents	**Baseline**	**19**	**114**	**245**
	---------- $\mu g \cdot m^{-3}$ ----------			
Ammonium sulfate	3.07	6.83	6.83	6.83
Ammonium nitrate	0.37	0.71	0.71	0.71
Organic carbon	1.59	10.42	99.61	222.60
LAC/Black carbon	0.34	0.68	6.49	14.50
Fine soil	0.22	0.36	0.36	0.36
Coarse mass	4.66	5.78	11.40	24.50

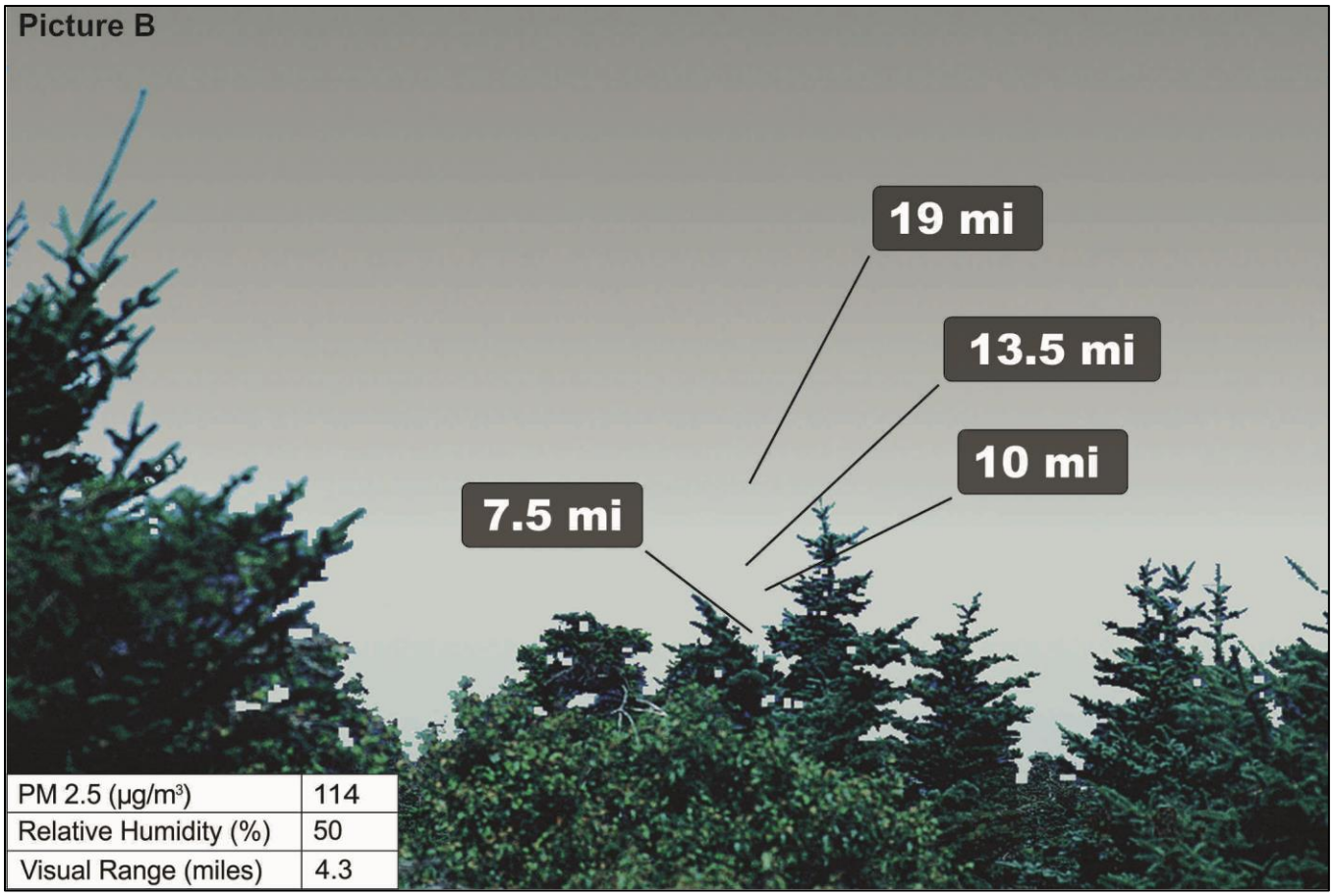
Table 25—Visual range as a function of $PM_{2.5}$ concentration and relative humidity in Acadia National Park, ME

$PM_{2.5}$ Concentration	Relative Humidity	Visual Range	
$\mu g \cdot m^{-3}$	*percent*	*miles*	*km*
<5 (baseline)	50	66.5	107.0
19 (picture A)	50	25.0	40.2
	60	22.9	36.9
	70	20.7	33.3
	80	18.4	29.6
114 (picture B)	50	4.3	7.0
	60	4.2	6.8
	70	4.1	6.5
	80	3.9	6.3
245	50-60	1.9	3.1
	70	1.8	2.9
	80	1.7	2.7

ACADIA NATIONAL PARK, ME






Picture B
19 mi
13.5 mi
10 mi
7.5 mi
PM 2.5 (µg/m³) 114
Relative Humidity (%) 50
Visual Range (miles) 4.3

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